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An Approach to Dealing with the Difficulties Undergraduate Chemistry Students Experience with Stoichiometry

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ABSTRACT

Chemistry for first year students has been identified by Tshwane University of Technology as one of the subjects with a low pass rate. It is apparent that students often memorize formulae and definitions, without understanding the underlying concepts required to work with abstract units of measure. We have found that the majority of students at this university are unable to balance reaction equations satisfactorily. They are also unable to predict the reaction yield, or identify limiting reagents. It is imperative that these and other related problems are overcome before any meaningful change to the high failure rate at first year level will be realized. All conventional forms of lecture presentation failed to make any significant impact on the success rate. Structured worksheets were developed and used, together with tactile models, to address the problems and the initial findings showed a marked improvement. It was discovered that the students' problems originated from their inability to understand the meaning of subscripts and coefficients in chemical equations. The worksheets and the impact they have made on the students' understanding of stoichiometry are shared in this paper.

KEY WORDS

Stoichiometry, limiting reagent, worksheets, tactile models.

1. Introduction

Attrition of students at universities is an undesirable problem common to tertiary institutions worldwide. The international trend is for governments to reduce funding and insist upon expedient throughput of students.[1] Graduates must be equipped with knowledge and skills that contribute towards economic growth and prosperity.

Chemistry is a subject involving fundamental scientific knowledge, reasoning skills, abstract concepts, and problem-solving calculations. Furthermore, the student is required to make the transition between macro and micro levels of matter, since the subject includes the study of interactions between indescribably small particles of nature, which cannot be envisaged or measured by simple physical means. As such, the subject is frequently regarded as difficult. This perception is compounded when the basic concepts are not thoroughly embedded before moving to problems which require more complex reasoning skills. We have identified stoichiometry as one of the areas causing confusion amongst students. Adequate understanding of reaction stoichiometry is fundamental to the study of chemistry and irrevocably entwined in the ability to complete laboratory work of an acceptable standard. Several other researchers in the field have reported similar difficulties with first year students and their results will be compared with those of the current study.

Although unfortunate, it remains a reality in South Africa that past imbalances in the education system continue to perpetuate poorly resourced schools and inadequately skilled teachers, particularly in the fields of mathematics and science. According to the TIMMS report.[2] South African learners achieve far lower scores for solving basic mathematical and literacy problems than those of any of the other countries included in the study. Learners from poorer southern African countries, such as Lesotho and Swaziland, can read and count better than South African learners.[2] It seems that despite all efforts to bring about transformation in school education, the quality of mathematics and science teaching is of a lower standard in South Africa than in other African countries.[3] To exacerbate this disadvantaged position, many of these students have English (the medium of instruction) as second or third language.[4] The cumulative effect of these factors creates a situation where students enter university with an inadequate knowledge of either the basic symbolic language of chemistry, or the fundamental principles which underpin the study of chemistry. Innovative interventions are required for these deficiencies to be addressed successfully.

Tshwane University of Technology (TUT) has introduced a Foundation Chemistry programme in an attempt to improve the pass rate for first year chemistry. In addition to chemistry, mathematics, English language, physics and basic computer skills are taught for the first six months of the academic year. Those students who successfully complete this programme are then admitted to the first year chemistry programme. The Foundation Chemistry programme overlaps with the first part of the Chemistry 1 syllabus but is covered at a slower pace. In spite of the introduction of this extended programme, the pass rate for Chemistry 1 has improved only marginally.

Two groups of Foundation Chemistry students are usually admitted to the university at the beginning of every academic year. Grades achieved by these students during the Grade 12 final examination fall within a very narrow range. The conceptual understanding of these students has been assessed for 2007 and 2008 using Mulford and Robinson's[5] Chemical Concepts (MCC) test. The average scores determined using this tool were similar for students in both groups. This allowed us to develop intervention techniques which could be implemented to one of the groups while the other group could be used for comparison. One of the questions which gave the worst results was concerned with stoichiometry. In addition to the classroom tuition delivered

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to all Foundation and Chemistry 1 groups, a computer-assisted intervention, designed primarily for self-study, was tested during a pilot study in 2007 and then implemented to one of the Foundation Chemistry groups during the first semester of 2008. Although some improvements were observed, fundamental concepts such as phase changes in water remained problematic. Many factors, including insufficient motivation, could have played a role in the unacceptably small improvement observed following the computer-assisted intervention. It was thought that structured worksheets, together with tactile models, which require more active participation by students, may be a more suitable delivery mode. The implementation of structured worksheets as an alternative intervention to address poor conceptual understanding of stoichiometry is the topic of this paper.

2. Background of the Study

One of the possible reasons for the high drop-out rate of first year entry level students at tertiary institutions is their inability to achieve more meaningful understanding of the required knowledge. This problem is not unique to universities in South Africa or to TUT in particular.[6,7] A number of factors have been identified which influence the ability of students to acquire the skills and knowledge needed successfully to complete the chosen programme. These factors include prior learning background,[8] academic literacy skills,[9,10] limited funding, and lack of commitment to studies.[11] Cassels and Johnstone[12] found that rephrasing problems in simple terms using basic vocabulary resulted in a higher percentage of students being able to solve the problems. However, Gabel and Sherwood[13] and Gabel and Samuel[14] found that when chemical terms such as molarity and mole were replaced with familiar terms such as concentration and dozen, it became apparent that the lack of success was not due to the terminology, but rather to a poor understanding of the fundamental processes involved.[15] These contrasting results reflect the complex number of variables which have direct bearing on difficulties students encounter with problem solving. The use of vocabulary the learner is accustomed to, and additional mathematics teaching, although useful, is not enough. Conceptual scientific knowledge, in addition to both procedural mathematical knowledge, and the language skills to understand exactly what is required to solve any given problem, are all factors crucial to success. Several researchers[15–17] have found that students often lack these skills and then attempt to memorize formulae and apply exactly from memory. These methods are only successful when similar problems are presented but, once the problem is approached from a different perspective, or too many steps are involved, such methods do not work. Students must be enabled to think and reason through problems in chemistry, rather than rely on memorization, which is inadequate and restrictive to meaningful progress.

Johnstone[18] formulated a theory describing the stages of learning as being first essentially embedded at the macro level before moving to the micro level. Once this progression has been made it may be expected of students to understand and inter-relate within the relatively abstract, symbolic language of chemistry. In accordance with this theory we have designed worksheets to move back to the macro level where students can see, feel, touch and manipulate concrete models before working with reaction equations. We have explored the use of structured worksheets together with Lego blocks for model building as a means to increase conceptual understanding of basic chemistry concepts, such as stoichiometry. This decision was influenced by the contribution of two well known researchers. The Swiss psychologist, Piagét, described the four stages of human cognitive development as sensory motor, pre-operational, concrete and formal operations. Of importance to this study is Piagét's belief that when concrete reasoning is not fully established, development to the formal operational level, where abstract reasoning is established, will be inhibited.[19] Adding further substance to Piagét's work, Johnstone[18] maintained that it is impossible for students to translate among three levels of thought, which he described as the macro, or tactile level, the sub-micro, atomic and molecular level and finally the abstract symbolic language commonly used in chemistry.

3. Sample Population

A Foundation Programme offers the opportunity of ensuring that basic skills and knowledge are firmly embedded before the student starts the first year of tertiary education. Problems with the intricacies of chemical reactions are common to all first year chemistry students,[7,16,20] not only those admitted to the Foundation Chemistry programme. This study examined the entire cohort of first year chemistry students at Tshwane University of Technology (TUT), encompassing those who registered for the programme Chemistry 1 ($n = 393$), as well as those registered for Foundation Chemistry ($n = 153$), during the 2008 academic year.

All of these students had completed three years of senior high school chemistry incorporated as a component of the subject Physical Science. The Foundation Chemistry students passed the subject at Grade 12 level, but the grades achieved were insufficient to allow admission to the mainstream chemistry programme (a final score of as little as 30 % can be sufficient to pass the subject). These students were required to pass the six-month Foundation Chemistry programme before being admitted to the Chemistry 1 programme.

4. Research Methodology

4.1. Research Design

This project forms part of continuous research designed to improve the success rate of first year chemistry students at TUT. This particular cycle of the study investigated the fundamental conceptual chemistry knowledge of all students registered for either Chemistry 1, or Foundation Chemistry, at the commencement and conclusion of the first semester 2008. The Chemistry 1 groups were divided into three different intact classes described as C1, C2 and C3. In order to compare normal lecture presentation with two, different, targeted intervention techniques, the Foundation Chemistry students were divided into two groups, referred to as the Experimental Group, FE, and the Comparison Group, FC (two classes of approximately 50 students each). The division into groups was done according to both the size of the available venues and to allow smaller class sizes. No measures were taken to ensure that FE and FC were matched in terms of gender, but the standardized proficiency test written by all prospective students as part of the entrance requirements of the university indicated the same distribution of marks for both FE and FC students. The proficiency test includes indicators for both ability and motivation. Figure 1 gives an overview of the design, showing clearly the different paths of the FE and FC cohorts.

4.2. Data Collection Tools

The study made use of the standardized 22-item multiple choice MCC test[5] which was applied as both a pre- and a post-test to determine the level of fundamental chemistry knowledge the students presented upon entry to the university,

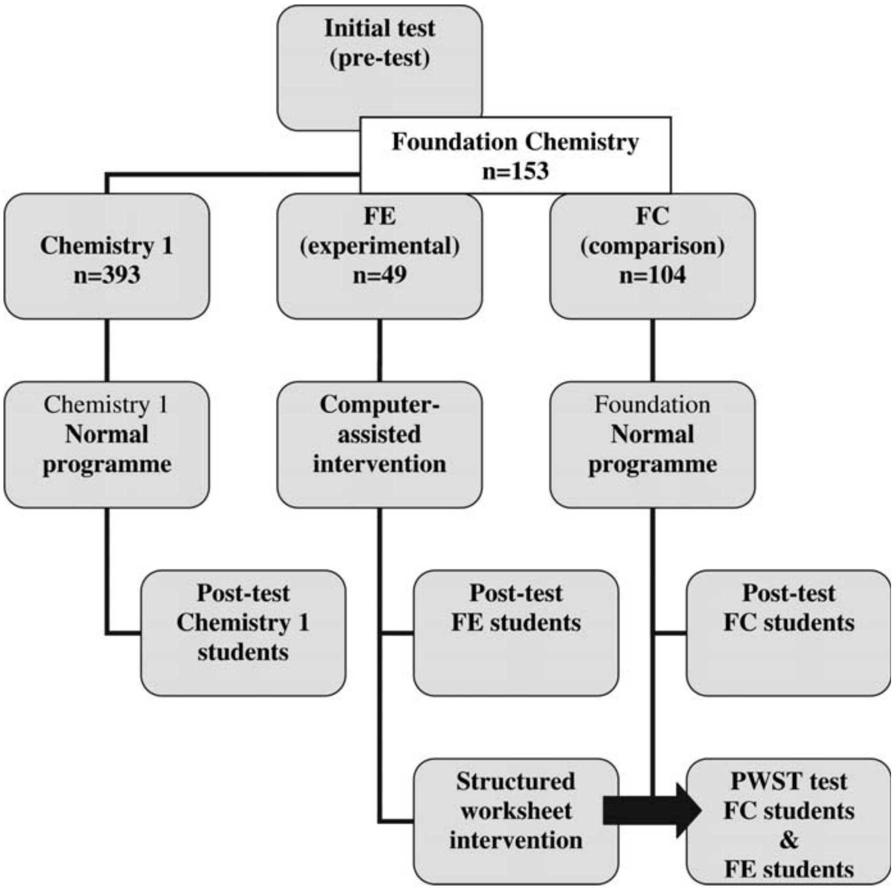


Figure 1 The research design, an overview of the steps involved.

and then again upon completion of the programme. Several shortcomings in their conceptual understanding of chemistry had been previously identified and a computer-assisted intervention designed. This computer-assisted intervention was applied to the FE group only, while FC was used for comparison. Any change in students' levels of conceptual understanding after completion of the normal programme of tuition, with or without addition of the computer-assisted intervention, could then be determined. The MCC test[5] included questions relating to the concepts underpinning stoichiometry as well as questions involving the balancing of chemical reaction equations together with the concepts of both limiting and excess reagent. These topics were covered during the normal programme of lectures, but students still experienced difficulty with coefficients and subscripts and were unable to identify limiting reagents. Structured worksheets and 'Lego' blocks, where each coloured block depicted an atom, were used by the FE group of students, to help them envisage the breaking and reforming of chemical bonds between molecules. It was hoped that in this way the concepts would be more readily understood. A post worksheet test (PWST) comprising only four multiple choice questions was taken after completion of the worksheets. The questions were directly related to the stoichiometry question taken from the MCC test and investigated the students' understanding of the concepts of limiting and excess reagent. The students' answers to the stoichiometry question indicated an incomplete understanding of these fundamental concepts which are crucial to the correct analysis of chemical reaction equations. Incomplete, or inadequate, understanding of limiting and excess reagents would contribute towards the difficulty students experience with this problem. The FC group completed the PWST, even though these students had not been exposed to the worksheets.

The worksheets were validated by the Chemistry 1 lecturers at TUT with respect to their suitability and fit with the syllabus requirements of the programme. Two external experts in the field also agreed to validate the worksheets, according to the same parameters. The PWST was developed by the Chemistry 1 lecturers at TUT and validated externally.

4.3. Stoichiometry Question

Figure 2 is a diagrammatic representation of the stoichiometry question used in the pre- and post-tuition test, together with the five possible distracters. This is one of the questions in the MCC test[5] and was deliberately selected because it was one of the questions with which students had experienced difficulty. The question was not directly addressed during the computer-assisted intervention. The identical question was used again in the worksheet intervention which meant that the results could be compared. Figure 2 shows the percentage of students who gave each of the possible answers, distracter (d) being the correct one. Foundation Chemistry groups are combined and marked F (a) for the pre-test and F (b) for the post-test (n = 153). Chemistry I groups are also combined and indicated as C (a) for the pre-test and C (b) for the post-test (n = 393).

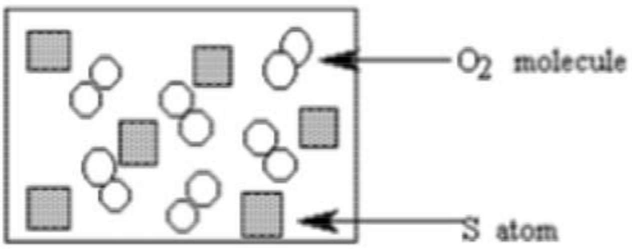
To show that the results shown in Fig. 2 are not unusual for first year chemistry students in general, the percentages obtained in the pre-test results of Mulford[5] (n = 905), indicated by M, and those of Potgieter[21] (n = 185), marked P, are also included.

4.4. Worksheet Intervention

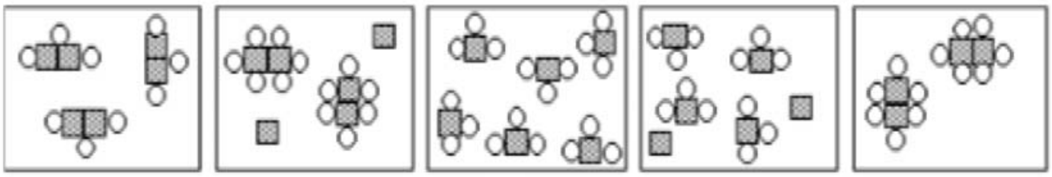
The proposed worksheet intervention model, which is represented in Fig. 3, serves to summarize the manner in which the worksheets were designed and the strategies involved to achieve adequate understanding. The model is based on one

The diagram shows a mixture of S atoms and O_2 molecules in a closed container.

STARTING MIXTURE



Which diagram shows the results after the mixture reacts as completely as possible according to the equation: $2S + 3O_2 \rightarrow 2SO_3$



(a) (b) (c) (d) (e)

	(a)	(b)	(c)	(d)	(e)
F (a)	24%	10%	12%	**4%**	50%
F (b)	22%	14%	9%	**11%**	43%
C (a)	18%	10%	13%	**5%**	53%
C (b)	16%	11%	16%	**9%**	48%
M	14%	23%	15%	**11%**	37%
P	9%	10%	28%	**8%**	44%

Figure 2 Comparison of test results for the different distracters where the option marked (d) and marked in bold typeface is the correct selection. This question was used in both pre- and post-testing as well as in the worksheet.
Key: F (a) and F (b) = Foundation Chemistry students pre- and post-test results
C (a) and C (b) = Chemistry 1 students pre- and post-test results
M = Mulford and Robinson's[5] (MCC test) pre-test results
P = Potgieter, Rogan and Howie's[21] test results

used previously with worksheets addressing the phase changes in water[22] and is based on the work of other researchers in the field.[5,17,23] The worksheets were designed to be used with small groups of only eight students per facilitator and were therefore intended to enhance student motivation, in addition to requiring students to be more actively involved with their own learning. It was hoped that this intervention would alleviate problems associated with deficiencies in both linguistic and prior learning areas. All steps followed are clearly shown in the model.

During the first step, students considered the question together with four possible answers. Facilitators then demonstrated the 'Lego' blocks, which were used as models, by illustrating not only the question but all possible distracters as well. The students then selected an initial answer. Facilitators helped them to work through the supporting theory included in the worksheets. Each student worked with his/her own set of 'Lego' blocks. A revised answer could subsequently be selected and the PWST was completed immediately after the intervention.

4.5. Worksheet Questions

Two questions were used in the worksheets and for each of these questions the same process was followed, as illustrated in Fig. 3. The first question is included in Fig. 4 and involved the formation of water from hydrogen and oxygen gas. It is a representation of the worksheet developed by Gummow,[24] which was based on previous research by Mulford[5] and Yitbarak.[23]

In Question 1 of the worksheet, the starting materials would produce exactly two molecules of water; no limiting or excess reagent was included. This was a very basic introductory question and it was hoped that by using and demonstrating the coloured 'Lego' blocks the students should have little difficulty.

The second question in the worksheets was taken directly from the MCC test[5] and is an extension of the same question which was used in the pre- and post-tuition test written by all the first year students used in this study.

4.6. Test Applied after the Worksheets (PWST)

Both groups of Foundation Chemistry students wrote the four question multiple choice, PWST, test based on the stoichiometry worksheet intervention, although only one of the groups had actually been exposed to the intervention. The FE group completed the test immediately after the worksheet intervention, while the comparison group (FC) wrote the same test during their lecture session, later on the same day.

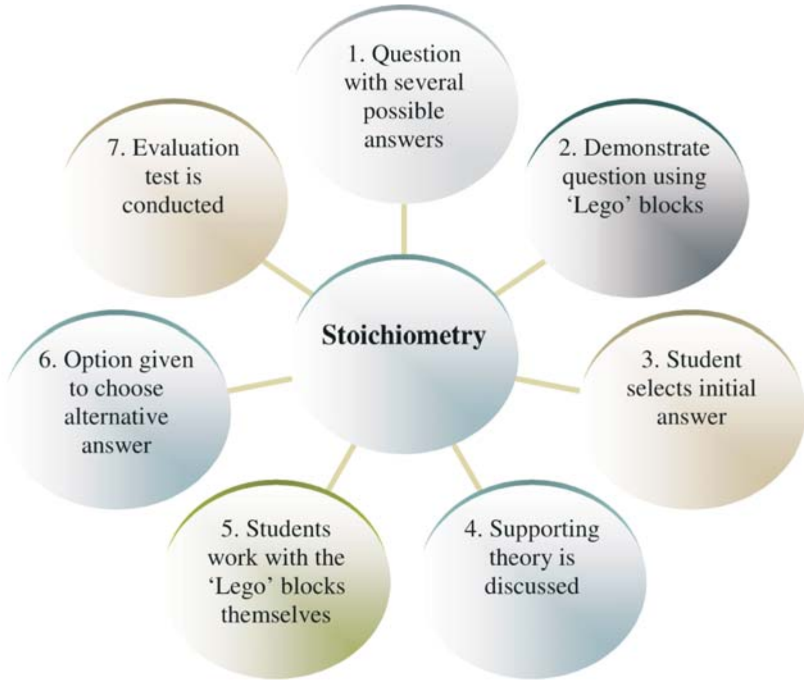


Figure 3 The intervention model showing the seven stages incorporated in the worksheets.

5. Results

5.1. Pre- and Post-test

Initial testing was done using the MCC test[5]. The pre-intervention test results of the entire cohort of first year Foundation Chemistry and Chemistry 1 students indicated that these students shared common misconceptions regarding physical and chemical changes of molecules and atoms. These misconceptions are the same as those identified by other researchers in the field.[5,17,21] The most popular distracter selected by the first year students was one which clearly emphasizes the confusion experienced with coefficients and subscripts. The product of the reaction equation was given as $2SO_3$ and the diagrammatic representation students most frequently linked to this was S_2O_6. This appears to be the result of a mathematical calculation which is an inaccurate interpretation of the symbolic language of chemistry. Both the Foundation Chemistry and Chemistry 1 students investigated recorded noticeably lower pre-test correct scores than either Mulford and Robinson[5] or Potgieter *et al.*,[21] but on post-testing, after formal tuition, they were at approximately the same level. All of these pre- and post-test results are clearly illustrated in Fig. 2.

The *t*-test results of the pre- and post-tuition evaluations of all the students using all 22 questions from the chemistry concepts test[5] is given in Table 1. Each correct answer carried one mark, resulting in a total score of 22. The mean score for each of the groups ranged from 4.25 (19 %) to 6.96 (32 %). The FE group, which had received the intervention, showed the greatest improvement in their mean score for the post-tuition test. The actual average score for the post-test of this group was the same as that of the other Foundation group, but their pre-test scores had been lower. Some improvement was measured for each of the Chemistry 1 groups, C1, C2 and C3, as well as for the other Foundation group, FC. This in essence means that computer-assisted intervention resulted in only marginal improvement when compared with the results obtained by the conventional forms of lecture presentation alone. Statistically, all groups achieved a significant improvement, on post-testing, irrespective of the mode of content delivery. No statistically significant difference was evident between the normal programme of lecture presentation and the additional computer-assisted approach. In spite of the statistical analysis indicating that the level of improvement between the pre- and post-tuition test was significant, irrespective of the instructional mode, the level of improvement in many of the fundamental concepts was inadequate, and the response to the question on stoichiometry was disappointing.

Table 1 *t*-test comparisons of pre- and post-test scores at 95 % confidence level (CL) recorded by the FE group.

Comparison	Mean	t_0 [a]	df [b]	Significance at 95 % CL
C1 pre-test	5.20	–2.832	89	0.006
C1 post-test	6.36			significant
C2 pre-test	5.16	–2.003	158	0.007
C2 post-test	5.92			significant
C3 pre-test	5.60	–2.241	143	0.000
C3 post-test	6.96			significant
FE pre-test	4.25	–3.965	48	0.000
FE post-test	6.06			significant
FC pre-test	5.0	–3.151	103	0.009
FC post-test	6.05			significant

[a] t_0 critical value.
[b] df number of degrees of freedom.

5.2. Results for Question 1 in the Worksheets

The first question in the worksheets involved only starting reactants being re-formed into the end products, with no limiting or excess reagent involved. Figure 4 gives a complete representation of the question. It was explained to students that when the circles in the diagram were touching it represented a chemical bond and it was hoped that students would recognize the water molecule. Figure 5 shows the percentages of students who selected each of the distracters, option (c), marked with boldface type, being the correct one. According to the intervention model

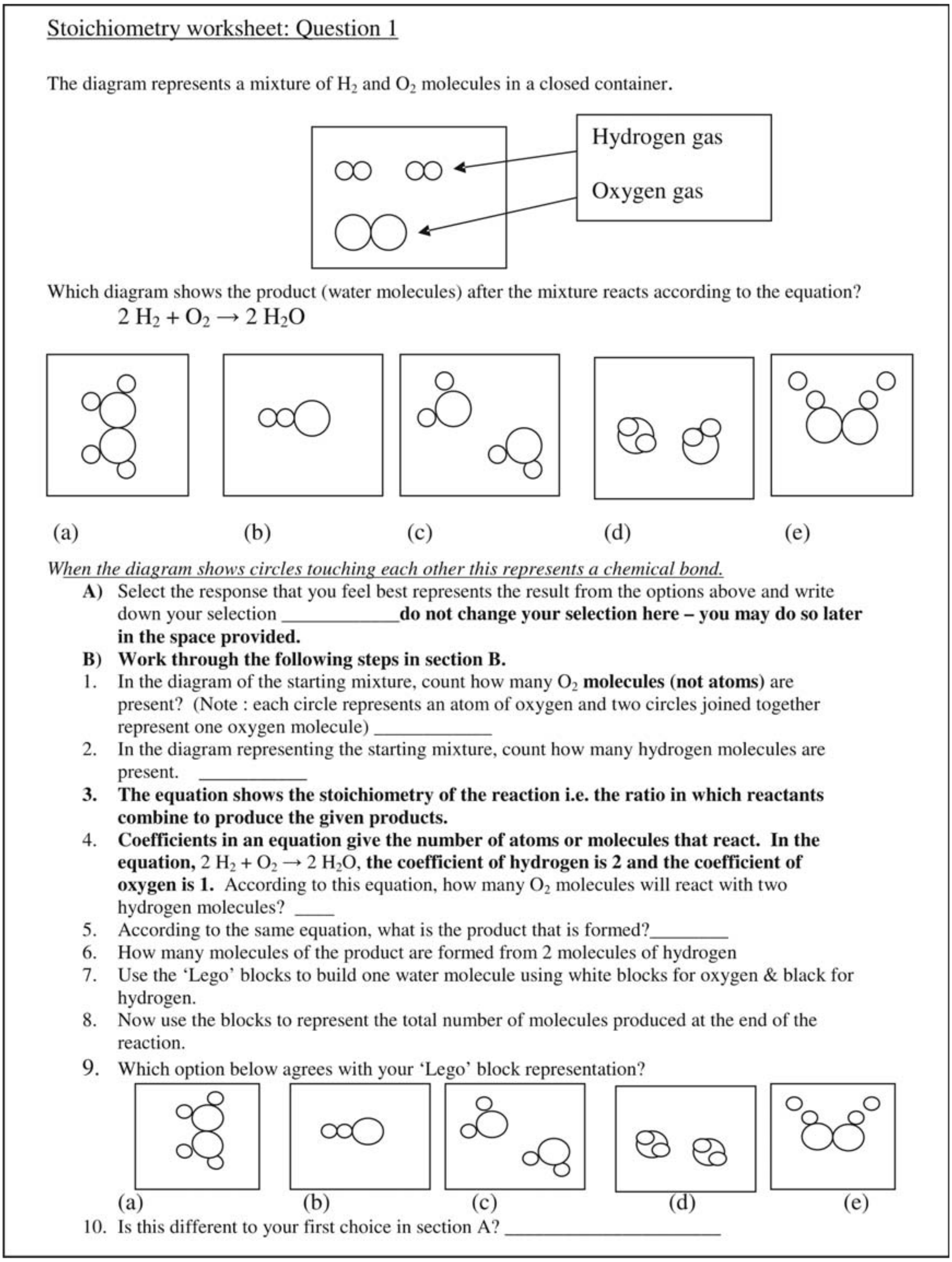


Figure 4 Question 1 of the structured worksheet illustrating different representations for the formation of two water molecules from the reaction of hydrogen gas and oxygen gas.

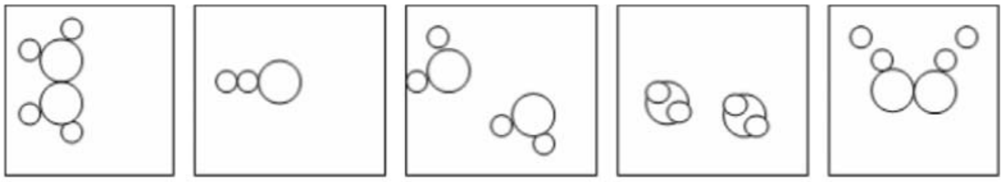
(Fig. 1) both the initial (i) and final (f) results are indicated.

From the results of this first question it is noticeable that no difference was recorded between the initial and final selections made by the students. Although students were asked not to alter their initial answer once they believed it to be incorrect they were observed by facilitators to have ignored the request and these answers were altered. It may also be noted that distracter (d) may be considered as representing the water molecule from a different viewing perspective. This means, in effect, that more than 80 % of the students do understand what a water molecule looks like.

5.3. Results for Question 2 in the Worksheets

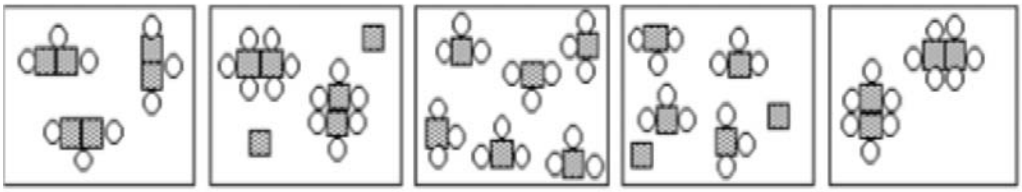
Question 2 was more difficult and included testing understanding of the symbolic language used in reaction equations as well as that of limiting reagents. After completing the worksheet the percentage of students giving each of the possible distracters was recorded and is illustrated in Fig. 6. Distracter (d) is the correct option and is shown in boldface type. Both the initial (i) and final (f) answers are given according to the intervention model presented in Fig. 3.

Facilitators were more diligent in ensuring that students did not alter their initial selection for this question. The percentage



	(a)	(b)	**(c)**	(d)	(e)
FE (i)	16	0	**77**	7	0
FE (f)	16	0	**77**	7	0

Figure 5 Responses, as percentages, for the experimental group (FE) to each of the possible distracters in question 1 of the worksheet regarding the formation of water.



	(a)	(b)	(c)	(d)	(e)
FE (i)	18	24	4	**39**	15
FE (f)	22	18	2	**43**	15

Figure 6 Responses, as percentages, for the experimental group (FE) to each of the possible distracters in question 2 of the worksheet, the stoichiometry question. Only the answers are shown since the question is the same as given in Figure 2.

of students able to indicate the correct distracter increased marginally after using the worksheet. It remains disappointing that once students have incorrect conceptual understanding it is extremely difficult to convince them otherwise and more than half of the students in this particular cohort still failed to provide the correct answer.

5.4. Results of the Post Worksheet Test (PWST)

This test was completed by all Foundation Chemistry students. The FE group completed it directly after the worksheet intervention while the FC group completed it during lecture time later on the same day. During the test, students were provided with rough paper and advised to make diagrammatic representations of the reactants and products referred to in the questions. It was pointed out to the students that diatomic molecules were represented by two circles just touching each other, while separate atoms of elements were represented by single squares not touching one another. These questions, together with the total answers, given as percentages, and prefixed by FE and FC to distinguish between the two groups, are given in Table 2. The correct distracter is marked in the third column and the correct answer is indicated by boldface type.

6. Discussion

The pre- and post-test results for the stoichiometry question indicate that the majority of students had serious problems with the underlying concepts related to stoichiometry. Only 4 % of the Foundation Group students and 5 % of Chemistry I students selected the correct answer at the start of their study year (Fig. 2). After completion of the first semester this did not improve much either; only 11 % of the Foundation Chemistry group and 9 % of the Chemistry I students selected the correct answer (post-test). Other researchers in the field had achieved equally poor results when their students enrolled at university;[5,21] these results are presented in Fig. 2. This merely serves to underscore the need to overcome the common problems students present in this regard.

The first question used in the worksheet intervention was very basic and it was expected that students would be well acquainted with the usual two dimensional representations of the water molecule commonly found in chemistry textbooks. It was noted that even after taking time to complete the worksheet with the aid of the 'Lego' blocks, students often retained their misconceptions so that the percentage of students giving the correct answer remained unchanged. This correlates with the findings of other researchers in the field who noticed the difficulty in changing deeply embedded misconceptions that students experience.[25,26] An average of 77 % of the students could identify with the correct answer, and if option (d) was included as correct when viewed from a different angle 84 % of the students were correct. At this level all of the students should have been able to identify the correct answer.

The second question in the worksheet was more difficult, and required students to understand the concepts of limiting and excess reagents, in addition to simply balancing a chemical equation.

The introduction of the worksheet intervention showed a marked improvement in results, as measured by the post worksheet test (PWST). The results of the PWST, conducted immediately after the worksheet intervention had been completed, are now analyzed, first by the overall average followed by a brief summary of each question. The correct distracter (average of all questions) was selected by 75 % of the students who had used the worksheet intervention (FE) compared with 47 % of the comparison group (FC) who only wrote the test. The four questions were arranged in order of perceived increasing complexity; the first question merely required students to define what a limiting reagent is. The most frequent mistake, 17 % FE and 26 % FC, was to indicate that the reactant with the fewest

Table 2 PWST multiple choice test questions completed by two groups of Foundation Chemistry students (correct selection is in boldface type).

FE	FC	1.	The limiting reactant in a chemical reaction is the reactant that
75	**47**	X	**is used up at the end of the reaction.**
5	18		is left over after the reaction.
3	9		has the largest number of atoms.
17	26		has the fewest number of atoms.
FE	FC	2.	How many water molecules (H_2O) can be produced from 6 molecules of hydrogen gas reacting with 6 molecules of oxygen gas? Which reactant is limiting?
38	**26**	X	**6 water molecules, hydrogen is limiting**
25	23		3 water molecules, oxygen is limiting
19	28		3 water molecules, hydrogen is limiting
15	23		12 water molecules, oxygen is limiting
FE	FC	3.	16 atoms of carbon (C) react with 10 molecules of hydrogen gas (H_2). How many molecules of methane (CH_4) will be formed, and what will be left over?
18	14		8 molecules of methane formed, 2 molecules of hydrogen left over
64	**30**	X	**5 molecules of methane formed, 11 atoms of carbon left over**
18	34		4 molecules of methane formed, 12 atoms of carbon and 2 molecules of hydrogen left over
0	22		10 molecules of methane formed, 6 atoms of carbon left over
FE	FC	4.	When aluminium (Al) reacts with chlorine gas (Cl_2), aluminium chloride is formed according to the following balanced equation: $2Al + 3Cl_2 \rightarrow 2AlCl_3$ If 4 atoms of aluminium react with 9 molecules of chlorine gas, which reactant is limiting and how many more atoms/molecules would be required to use up all the reactants?
8	20		Chlorine is limiting, 1 more molecule is needed
10	30		Chlorine is limiting, 2 more molecules are needed
58	**25**	X	**Aluminium is limiting, 2 more atoms are needed**
24	25		Aluminium is limiting, 4 more atoms are needed

atoms was limiting. The second question was not expected to present much difficulty, since it dealt with hydrogen and oxygen combining to form water. It was, however, poorly answered by both groups, FE 38 % and FC 26 %, with no obvious frequent mistake. The third question was answered well by the FE group with 64 % having the answer correct compared with the FC group with only 30 % correct. For the fourth question 58 % of the FE group selected the correct answer and a further 24 % correctly identified the limiting reagent. In the FC group no obvious trend was apparent with half of the group identifying the wrong limiting reagent and only 25 % selecting the correct answer.

7. Conclusions

The structured worksheets made a noticeable impact on the learning situation and considerably improved the level of understanding of the concepts addressed. These worksheets will now be integrated into the introductory phase of the first year chemistry programme as part of the tutorial work. The 'Lego' block approach should be encouraged since it really helped the students to understand the difference between coefficients and subscripts in reaction equations. A further positive result of using these blocks was to help students correctly to identify the limiting reagent in stoichiometric problems. More of these worksheets will be developed in order to target other identified problem areas within the first year chemistry programme. The results of this work will be presented in a future paper.

Finally, the approach which has been most successful in dealing with the problems first year students experience with stoichiometry has been one which takes them back to concrete models, which they can use to incorporate tactile senses. This is because students cannot visualize what happens at the particulate level, which deals with atoms and molecules, and students benefit from using suitable physical models to facilitate the development of abstract thought processes. This is an important prerequisite step needed to improve understanding of the symbolic representations used in chemistry and links with Piagèt's[19] belief that only once the concrete level has been firmly embedded can abstract reasoning be fully established. When students fail to understand basic terms it is hardly surprising that they fail to balance chemical equations, since they cannot even decide exactly what product is being formed. It merely exacerbates the issue when considerations of limiting reagent come into play and the students are evidently confused. More attention must be given to embedding understanding at a level where students can see, feel and touch, before moving too quickly to more abstract symbolic representations, which are commonly used to explain what is happening at the atomic level of matter. The use of models makes it easier for students to construct their own diagrammatic illustrations, and from there to interpret other more generally used textbook representations of matter. The findings of this article represent an important milestone on the road to improving understanding of the complexities of chemistry. Once students overcome their difficulties with basic concepts, the enjoyment of chemistry becomes a reality, and will kindle the desire towards life-long learning.

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