Students' Problem Solving Strategies in Stoichiometry and their Relationships to Conceptual Understanding and Learning Approaches

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Introduction

Stoichiometry is one of the most basic, central, yet abstract topics in chemistry. It is essential for understanding quantitative and qualitative aspects of chemical reactions as well as for solving many types of problems in high school chemistry. Moreover, one body of research findings highlight the importance of conceptual understanding for successful problem solving and qualitative thinking in chemistry and suggest that students' inadequate and incorrect conceptual knowledge impede successful problem solving in stoichiometry (BouJaoude, 1994; Harmon, 1993; Niaz, 1995b), while other studies have demonstrated an over-reliance on using algorithms to solve problems (Huddle & Pillay, 1996; Lythcott, 1990; Nakhleh, 1993; Nakhleh & Mitchell, 1993; Pickering, 1990; Sawrey, 1990; Staver & Lumpe, 1995; Tullberg, Strömdahl, & Lybeck, 1994). As a result, since teaching stoichiometric calculations is a difficult task (Schmidt, 1990), new instructional approaches and methodologies should be used in implementing curricula meant to prepare meaningful learners in chemistry; a situation which requires an understanding of students' problem solving strategies in chemistry in general and more specifically in stoichiometry.

According to Hayes (1981) "whenever there is a gap between where you are now and where you want to be, and you don't know how to find a way to cross that gap, you have a problem …Solving a problem means finding an appropriate way to cross the gap"(p. i). The definition of a problem is relative. A problem for one person might be a routine exercise for another; it all depends on the individual's knowledge and expertise (Hayes, 1981). Moreover, problem solving is meaningful and conceptual rather than merely algorithmic. Algorithmic problem solving requires application of preexisting procedures where learning and problem solving may not occur (Shuell, 1990). Meaningful problem, on the other hand, requires the use of algorithms as well as conceptual knowledge to obtain correct answers (Schmidt, 1997). Different approaches can be used to solve a problem depending on a variety of factors such as the nature and difficulty of a problem and the expertise and relevant knowledge of the problem solver (Hayes, 1981). According to Barnsford and Stein (1984) and Hayes (1981) the five basic approaches to problem solving are working backwards, breaking a problem into parts, working systematically, solving problems by analogy, and using procedural and conceptual knowledge. In this study, the focus was on topic-specific problem-solving strategies rather than on general and content-free approaches.

Researches have investigated strategies that students use during problem solving in chemistry as well as the relationships between conceptual understanding and problem solving (e.g. Harmon, 1993; Mason, Shell & Crawly, 1997; Niaz, 1995a; 1995b; Shaibu, 1992; Stanger & Greenbowe, 1997). Findings of this research indicated that students' problem solving in chemistry ranged from being entirely algorithmic to conceptual: It was algorithmic when conceptual knowledge was missing and conceptual when conceptual knowledge was available and when algorithms were stored meaningfully in memory. Moreover, research results indicated that problem solving was a function of the adequacy of conceptual and procedural knowledge. In actual fact, in many situations there was a strong association between faulty procedures and misconceptions. Finally, research showed that conceptual problem solvers were more efficient because they used less time and fewer steps to solve problems.

A number of researchers have investigated problem-solving strategies in stoichiometry. For example, Schmidt (1990, 1994) developed stoichiometry multiple-choice items that were used to identify students' problem solving strategies. Atwater and Alick (1990), on the other hand, used interviews to study the nature of college students' strategies when solving stoichiometry problems about mass, moles, volumes, and balancing equations.

Research in different areas in chemistry and in other subjects has established the existence of positive relationships between students' meaningful learning approaches and their achievement in science (BouJaoude, 1992; BouJaoude & Giuliano, 1991; Broathen & Hewson, 1989; Cavallo, 1991; Cavallo, 1992; Cavallo & Schafer, 1994; Cavallo, 1996; Chan & Bereiter, 1992; Lee & Anderson, 1993; Rukavina, 1991). According to Ramsden (1983) and Woods, Hrymak, & Wright (2001) meaningful learners have a deep approach to learning. They tend to build a holistic description of content, reorganize new content by relating it to prior knowledge and/or to personal experiences, are inclined to use evidence, and maintain a critical and a more objective view. Conversely, rote learners are those who have a surface approach to learning. They have a propensity for memorization of facts and are motivated extrinsically by fear of failure rather than the need to learn and understand (Ramsden, 1983; Woods, Hrymak, & Wright, 2001). Ramsden (1995) affirms that the concept of approach depicts a qualitative attribute of learning. It relates to how students experience and organize the subject matter of a learning task, "it is about 'what ' and 'how' they learn, rather than 'how much' they remember" (p. 40).

Ramsden (1995), however, cautions against the mistaken assumption that an approach is a characteristic of the individual. According to Ramsden, an approach to learning represents what a learning task or set of tasks is for the student. Furthermore, "an approach is not about learning facts versus learning concepts; it is about learning just the unrelated facts versus learning the facts in relation to the concepts." (Ramsden, 1995, p. 45). Additionally, Ramsden (1995) and Ramsden, Martin, and Bowden (1989) suggest that content of the subject being learned and the learning approach are intimately linked because learning always involves learning specific content. Finally, Ramsden (1995) contends that approaches to learning are associated with learning outcomes. As a result, meaningful learners might exhibit better conceptual understanding and problem solving abilities than rote learners because they are efficient information storers and processors. Therefore, a study of the problem solving strategies of meaningful learners versus rote learners is worth conducting because of its potential contribution in helping students become better problem-solvers.

The present study is unique in that it dealt with conceptual understanding, learning approaches, and problem solving simultaneously. Two data collecting methods; a paper and pencil test and interviews, were used to describe and classify high school students' problem solving strategies in stoichiometry. The assumption was that a combination of data collection methods may provide a more valid description of student-generated correct and incorrect problem-solving strategies. Consequently, the purpose of this study was to describe and classify the strategies high school students use when solving stoichiometry problems and compare and contrast problem solving strategies of students with different learning approaches and different conceptual understanding levels.

Methodology

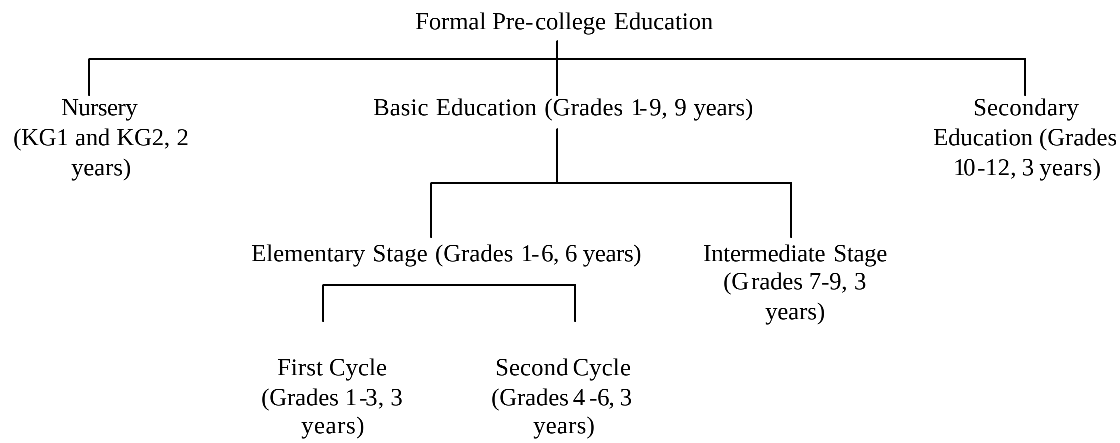
Design

The current study is a qualitative descriptive study; it attempted to describe individual students' problem solving strategies and compare them for students with different conceptual understanding levels and different learning approaches. Using a qualitative methodology was necessary because the purpose of the study was to understand students' problem solving strategies in depth rather than simply enumerating and categorizing them.

Description of the Lebanese Science Curriculum

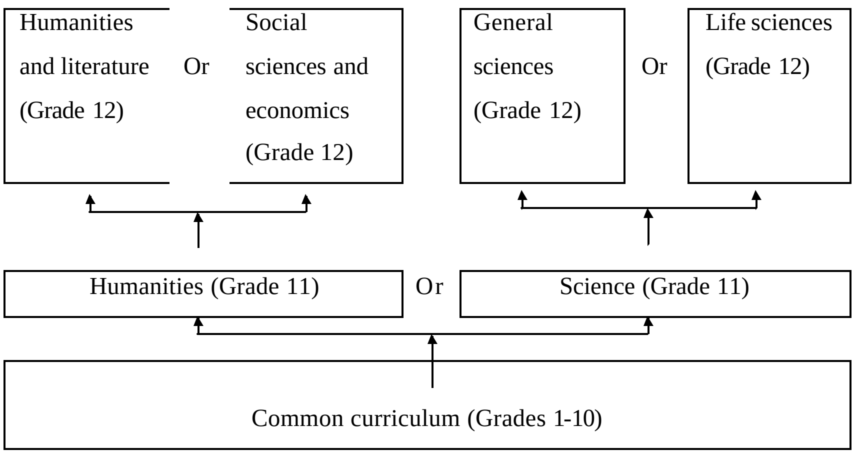
Formal pre-college education in Lebanon starts in the nursery stage (ages 4-6). The Basic Education stage (ages 6-15) consists of the Elementary Stage and the Intermediate Stage. The Elementary Stage consists of two three-year cycles while the Intermediate Stage consists of three years. The Secondary Stage consists of three years (Ages 15-18) (Figure 1).

Figure 1. Grades and Number of Years in Formal Pre-college Education in Lebanon.



The new Lebanese curriculum provides a common content for all students until Grade 10 (Figure 2). In Grade 11 students may choose to follow the Humanities Stream or the Science Stream. Those who choose the Humanities Stream may either continue with the Humanities and Literature Stream or follow the Social Sciences and Economics Stream in Grade 12. Students who choose the Science Stream in Grade 11 may choose the General Sciences Stream or the Life Sciences Stream in Grade 12. Each stream consists of a fixed number of courses that all students who choose the stream are required to complete. There is no possibility of elective courses within the stream. All students take science at all levels. However, the number of periods per week varies with the level and stream the student selects. Lebanese students start taking chemistry as a separate subject in Grade 7. The chemistry curriculum is common to all students until Grade 10. In Grade 11, students who choose the science stream continue taking chemistry in grades 11 and 12. Enrolling in the science stream, however, is has its requirements, one of which is high grades in all the sciences. Consequently, students in Grade11 are typically those who have high averages in the sciences and are interested in pursuing a science related career. Highly selective schools typically have more stringent requirements to allow students entry into the science stream.

Figure 2. Structure of the Lebanese Educational Ladder.



Subjects

Subjects in this study were forty students (20 females and 20 males, ages ranged from 16 to 20 years) enrolled in two sections of a Grade 11 (science stream) class in a highly selective private school in Lebanon in which English is the medium of science instruction. The same teacher taught the two sections. Students at this level take chemistry as part of their regular curriculum and are introduced to stoichiometry at the Grade 10 level. Two students (1 male, 1 female) were dropped from the study because they did not complete all the required tasks resulting in a final number of 38 students.

Data Sources

Three sources of data were utilized in this study: The Learning Approach Questionnaire, the Stoichiometry Test, and unstructured interviews.

Instruments

The Learning Approach Questionnaire.

(LAQ). The LAQ is a Likert-type instrument designed to measure students' approaches to learning ranging from meaningful to rote (Entwistle & Ramsden, 1983). The LAQ is based on the Approaches to Studying Inventory (ASI), an instrument that was developed by Entwistle and Ramsden (1983). The ASI consists of 16 sub-scales that measure different orientations or approaches to studying. Six of the 16 sub-scales (25 items) were included in the LAQ used in this study: Deep Approach (4 items), Relating Ideas (4 items), Intrinsic Motivation (4 items), Surface Approach (6 items), Syllabus-Boundness (3 items), and Extrinsic Motivation (4 items). The selected items were modified to measure approaches to studying chemistry. This modification was minimal and involved changing the subject matter mentioned in items to 'chemistry". The internal consistencies of the sub-scales were reported by Entwistle and Ramsden (1983) as Cronbach alphas, and ranged from 0.47 for Relating Ideas up to 0.78 for Extrinsic Motivation. Cavallo reported Cronbach alphas ranging from 0.65 to 0.80 (Cavallo, 1998, personal communication). Examples of the items used in the LAQ are presented in Figure 3.

A 5-point Likert scale (A = always true to E = never true) was used for responding. Scoring was reversed for some of the items to control for response set. The questionnaire was piloted with a different group of high school students to make sure that they had no problems with the language. This piloting showed that students had problems with a few words; consequently these words were changed to ones that were not problematic. The average score on each sub-scale and the total average score were computed for each student. Z-scores were calculated and students' scores were put on a meaningful-rote continuum, where high scores fell towards the meaningful learning end. Then, students were divided into 3 groups: A group with meaningful learning approaches (MLA) (the highest 13 z-scores), a group with rote learning approaches (RLA) (the lowest 13 z-scores), and a group with intermediate learning approaches (ILA) (12 students). The questionnaire was piloted with a different group of high school students and adapted based on the results of the piloting.

Figure 3. Sample Items from the LAQ.

	Always true	More true Than untrue	Undecided	More untrue than true	Never true
I generally put a lot of effort into trying to understand things that at the beginning seem difficult.	A	B	C	D	E
As I am reading new material in chemistry, I try to relate what I already know on the topic.	A	B	C	D	E
While I am studying chemistry, I often think of real life situations to which the material I'm learning would be useful.	A	B	C	D	E

The Stoichiometry Problem Solving Test.

This test contained eight problems. Most of the problems consisted of two parts: One part to assess problem solving strategies and another to assess conceptual understanding. The problems were written in an increasing degree of complexity, knowing that the more complex problems required greater number of steps and relatively more conceptual understanding. Stoichiometry problems used in previous research studies constituted a part of this test while the rest were developed by the researchers. The concepts and principles measured by the test were: a) Molar quantity, b) Limiting reagents, c) Conservation of matter, d) Molar volume, and e) Coefficient ratios in a chemical equation. Two high school chemistry teachers and two science education professors reviewed the Stoichiometry Test and confirmed its appropriateness for Grade 11 students.

The stoichiometry test was given to two high school chemistry teachers other than the one involved in the study and to two science education faculty members for review and comments regarding the appropriateness of the test for Grade 11 students. All four reviewers concurred that the test was appropriate for Grade 11 students. The test was also piloted with a group of high school students at a school other than the one in which the study was conducted to determine the approximate time needed to complete the test and find out if the wording and difficulty level of the test items were appropriate for Grade 11 students. Students in the pilot study were able to complete the test in approximately 2 class periods. In addition, the students had problems with a few English words, which were changed to more appropriate ones.

The Unstructured Interviews.

Sixteen students participated in the interviews. These interviews were different for different students. The interview questions for a student depended on his or her problem solutions. The interviewed students were provided with their problem solutions and asked questions to justify a selected number of solution steps and explain others. A student's response to one interview question determined the subsequent question or questions in the interview. Nevertheless, the interview questions for the different students were similar in their format in that they referred to the problem solutions. The length of the interviews ranged between 25 and 45 minutes. They were tape recorded and transcribed for subsequent analysis.

Procedure

Observing the study setting.

The two class sections were observed for six periods each before the inception of the study. The teacher needed six periods to explain the topic of stoichiometry and give students practice in solving stoichiometry problems. The observations showed that the teacher used the same teaching methods and solved the same problems in both sections. In addition, the observations showed that teachers spent most of their time solving problems rather than explaining chemical concepts related to stoichiometry.

Administering the LAQ.

All students completed the LAQ early in the school year. Students took approximately ten minutes to complete this task.

Administering the Stoichiometry Test.

The stoichiometry test was administered to the students on two successive days around the end of the school year during the regular examination schedule of the school and as one of the Grade 11 regular chemistry tests. The test was split into two parts and each part was given to both sections on the same day. This was done for two reasons. First, the test was split to reduce student fatigue and drop in performance on the last test questions. Second, giving a two-period test would have disrupted the class schedule since there was no double period during the regular schedule.

Analysis of the Stoichiometry Problem Solving Test.

The test was analyzed for conceptual understanding and problem solving strategies. A concept-evaluation scheme developed by Abraham, Gzybowski, Renner, and Marek (1992) was adapted and used to analyze students' conceptual understanding (Figure 4). This scheme consisted of four categories: No Conceptual Understanding (NCU), Partial Conceptual Understanding (PCU), Sound Conceptual Understanding (SCU), and no response. The responses of each student were analyzed using the above scheme to find out the level of their understanding of each of the five concepts and principles included in the test items (molar quantity, limiting reagents, conservation of matter, molar volume, and coefficient ratios in a chemical equation). Moreover, misunderstandings in each of the concepts were identified. Consequently, each student got a number of scores on each concept depending on the number of questions in which the concept was addressed. Thus, a student got a score of 0, 1, or 2 (NCU, PCU, and SCU respectively) on each situation where the concept was present. Then, an average score on each concept for each student was calculated and the scores on all the five concepts and principles were summed up to a total score. The maximum possible score was 10. A total score of less than four designated NCU, a total score between four and seven (Four is inclusive) designated PCU and a total score of seven and above designated SCU. Then, the students were divided into three groups according to their total scores on the five concepts and principles (see Abraham et al., 1992).

Figure 4. Categories of Understanding for Conceptual Chemistry Problems

Degree of understanding	Criteria for scoring
No response	Blank, I don't know, I don't understand
No conceptual understanding	Repeats question, irrelevant or unclear response
Partial conceptual understanding and Partial conceptual understanding with specific misunderstanding	Responses that show understanding of the concept but also make statements which demonstrate a misunderstanding Responses that include at least one of the components of the valid response, but not all components
Sound conceptual understanding	Responses that include all components of the valid response

Students' written solutions in the stoichiometry test were analyzed and their problem-solving strategies were described and classified. The analysis was conducted as follows: Every one complete idea that moved the student further towards the answer of the problem, whether the answer was correct or not, was designated as one step. Every solution was analyzed in terms of these complete ideas, and strategies were described for each student according to the number of steps, their sequence, and also according to their conceptual meaning[1]. Note that what might have been a strategy for one problem might be a mere step for another. For example, if a problem asked for the limiting reagent, then finding the limiting reagent was a strategy comprised of a number of steps, whereas finding the limiting reagent might be only one step in a more complex problem.

Forming the Conceptual Understanding/Learning Approach Matrix.

The three groups of students with different learning approaches and the three groups with different conceptual understanding levels were used to form the following nine groups: NCU/RLA, NCU/ILA, NCU/MLA PCU/RLA, PCU/ILA, PCU/MLA, SCU/ RLA, SCU/ ILA, and SCU/MLA (Table 1), where RLA is Rote Learning Approach, ILA is Intermediate Learning Approach, MLA is Meaningful Learning Approach, NCU is No Conceptual Understanding, PCU is Partial Conceptual Understanding, and SCU is Sound Conceptual Understanding.

Table 1.

Groups of Students Based on their Learning Approaches and Conceptual Understanding.

Conceptual Understanding	Learning Approach		
	RLA	ILA	MLA
NCU	NCU/RLA	NCU/ILA	NCU/MLA
PCU	PCU/RLA	PCU/ILA	PCU/MLA
SCU	SCU/RLA	SCU/ILA	SCU/MLA

Interviewing the selected sample

Two students were selected for interviewing from each of the above nine groups. This was a purposive sampling, where the students who gave interesting or vague responses were chosen. A student was not interviewed about all the problems. Rather, the problems for the interview were selected according to their potential to provide more information about the student's conceptual understanding and problem-solving strategies, and this depended on the responses he/she provided on the written part of the test.

[1] "Conceptual meaning" denotes whether or not a step is correct if taken by itself.

Analysis of the Unstructured Interviews

The sixteen interviews[2], which were audiotaped, were transcribed word by word. The problem-solving strategies that were identified in the analysis of the test were used as guides in this phase of the analysis. However, any new strategy that appeared from this analysis was noted. Thus, the data from the interview transcripts were used to substantiate and validate the findings from analysis of the test. Finally, problem-solving strategies were compared and contrasted for students belonging to different categories identified earlier in the procedure section.

Results

This section presents students' misunderstandings, problem solving strategies, the correlation between students' conceptual understanding scores and their ability to solve problems correctly even when using algorithmic solutions, and the relationships between conceptual understanding, learning approach and problem solving strategies.

Students' misunderstandings

The number of students at each conceptual level for each concept was calculated (Table 2). The number of students was the largest for the Partial Conceptual Understanding level except for the concept of limiting reagent where most of the students had either No Conceptual Understanding or Sound Conceptual Understanding. The major misunderstandings that were identified were in the topics of molar quantities, limiting reagents, conservation of matter, molar volume of gases at STP, and coefficients of chemical equations. Below is a detailed descriptions of each of these misunderstandings.

Table 2

Number of Students at Each Conceptual Level for Each Concept

Concepts	No response	SCU	PCU	NCU
Molar Quantities	_	14	16	8
Limiting Reagent	_	15	6	17
Conservation of matter	3	9	16	10
Molar Volume of a gas at STP	3	6	27	2
Coefficients in the Chemical Equation	_	10	16	12

Note. "SCU", "PCU", and "NCU" stand for Sound Conceptual Understanding, Partial Conceptual Understanding, and No Conceptual Understanding respectively.
*Two students decided not to participate in the interviews.

Molar quantities

Around 40 % of the students calculated the molar mass of a substance by adding the atomic masses and then multiplying/dividing the sum by the number of moles of that substance or by its coefficient in the chemical equation. Moreover, two students multiplied the atomic masses to get the molar mass of the substance and two students found the molar volume of a gas at STP by multiplying 22.4 L/mol by the coefficient of the substance in the chemical equation. Around 14% of the students related the molar quantities of a substance to its coefficient in the chemical equation. For example, they calculated the molar mass as the mass of two moles ($2NH_3$ and $2CO_2$) rather than one mole (NH_3 and CO_2)

Limiting reagent

Four students did not find the limiting reagent, they simply chose one of the two reactants and worked with it. Four other students used as the limiting reagent the reactant, which was given in moles and not the one in grams because, as they reported, it was easier to work with moles. Other errors related to limiting reagents included attempting to find the limiting reagent when having one reactant only, comparing molar masses to determine the limiting reagent, saying that the limiting reagent is the substance that is in grams and not the one in moles because moles can vary whereas mass cannot, finding the limiting reagent only when the two reactants were given in grams, comparing the given amount of one reactant and the calculated amount of the other to find the limiting reagent, not dividing the number of moles of the two reactants by their coefficients in the chemical equation before doing the comparison to find the limiting reagent, and using the reactant in excess to find the amount of the product.

Conservation of matter

Six students considered the sum of the number of moles of the given reactants equal to the total number of moles of gases at the end of the reaction while four students did not include the excess amount of the reactant in the total mass in the closed container at the end of the reaction.

The molar volume of a gas at STP

Twenty one students (55%) used the 22.4 L/mol for water and solutions. One student used the 22.4 L/mol for a substance as it appears in the chemical equation; i.e. if ammonia is $2NH_3$ in the equation, then 22.4 L/mol is the volume of $2NH_3$. Two students put STP as a condition for using the formulas: $V_1/n_1 = V_2/n_2$ and n= V/molar V, where "V" is the volume and "n" is the number of moles. Also, students did not use the correct unit for the number 22.4.

Coefficients in the chemical equation

Some students did not understand the significance of the coefficients in the chemical equation. For example, 13 students (34%) used the formula $coeff_1/coeff_2 = V_1/V_2$ for liquid water and solids, and five students used the formula $mass_1/mass_2 = coeff_1/coeff_2$. Also, five students used mass, volume, or number of moles of $2NH_3$, 2CO, and $2CO_2$ instead of NH_3, CO, and CO_2. $M_1/M_2 = V_1/V_2$ was also used by three students where V is the volume and M is the molar mass.

Problem- Solving Strategies[3]

The students used a variety of problem solving strategies: Correct strategies (algorithmic strategies, efficient strategies, and messy strategies), incorrect strategies (incorrect strategies-incorrect answers and incorrect strategies-correct answers), and incomplete strategies. A description of each of these strategies is provided below:

Correct strategies

A correct strategy was defined as a logical sequence of complete and correct steps that lead to a correct answer. The correct strategies were further classified into three sub-categories: Algorithmic, efficient, and messy.

Algorithmic strategies

The algorithmic strategy was a correct strategy and a sure way to the correct answer. It was similar to the strategies found in many textbooks.

Efficient strategies

The efficient strategy differed from the algorithmic strategy in being more conceptual, shorter, and a well thought out solution to the problem. This strategy often included students' own words, which often replaced a series of steps.

Messy strategies

A messy strategy included either irrelevant steps or a number of steps that merely elongated the path to the correct answer. The irrelevant steps, though correct sometimes, did not fit into the sequence of steps that led to the correct answer; they were isolated steps, the results of which were neither employed in finding the correct answer nor affected other steps

[3] Examples of the strategies are available in BouJaoude & Barakat (2000).

of the solution. In other messy strategies, some steps elongated the path from the problem to the correct answer.

Incorrect strategies

A problem solving strategy was considered incorrect if at least one of the following factors were present: Incorrect steps other than molar quantities, incomplete steps, or incorrect sequence of steps. The incorrect strategies were due mostly to conceptual mistakes. They showed misunderstandings of stoichiometry concepts such as the strategy using the formula: Mass of substance 1 over mass of substance 2 is equal to coefficient of substance 1 over coefficient of substance 2, which is a mis-conceptualization of the relation between the masses of different compounds and the significance of the coefficients in chemical equations. Moreover, most of the incorrect strategies were messy in the sense that they contained irrelevant or unnecessary steps that did not fit into the incorrect strategies. The incorrect strategies were further divided into two categories: Incorrect strategies-incorrect answer and incorrect strategies-correct answer.

Incorrect strategies-incorrect answer

They were the incorrect strategies that led to correct answers. As examples we have:

Incorrect strategies-correct answer.

Some incorrect strategies led to correct answers by chance. In Problem 7b, calcium carbonate was the limiting reagent and by using it, one can arrive to the correct answer. But, in this type of strategy, it was not used because it was the correct limiting reagent; instead, it was selected by chance because, according to the students, it does not matter whether HCl or $CaCO_3$ was used to find the amount of the product formed.

Incomplete strategies.

In the incomplete strategy, a student typically started to solve a problem correctly, but stopped one or two steps before getting to the correct answer.

It is worth noting that some solutions could not be categorized and some students skipped some problems.

Table 3 shows that students who solved the problems correctly used mostly algorithmic strategies followed by efficient strategies. Moreover, as the problems became more complex, students were less successful in using correct algorithmic strategies but resorted more to using efficient strategies.

Table 3

Percentage of Students for Each Type of Problem Solution for Each Problem Part

Problem	Correct Strategy			Incomplete Strategy	Incorrect Strategy		No Strategy		Missing Solution
	A	E	M	I	II	IC	N(1)	N(2)	0
P1a	97%	--	--	–	3%	--	--	–	--
P1b	87%	--	--	–	13%	--	--	–	--
P1c	53%	--	5%	–	29%	--	--	–	13%
P1c`	68%	--	3%	–	29%	--	--	–	--
P2a	84%	--	--	–	16%	--	--	–	--
P2b	–	8%	--	–	89%	--	3%	–	--
P3a	74%	--	--	8%	11%	--	8%	–	--
P3c	63%	11%	--	–	6%	--	5%	–	16%
P4	13%	24%	--	34%	11%	--	18%	–	--
P5a	13%	58%	--	–	11%	--	5%	–	13%
P5b	37%	18%	--	–	11%	11%	5%	–	18%
P6a	42%	45%	3%	–	3%	--	8%	–	--
P6b	–	13%	--	–	55%	5%	16%	3%	8%
P7a	37%	11%	3%	–	34%	13%	3%	–	--
P7b	37%	5%	3%	–	32%	13%	11%	–	--
P8a	37%	18%	3%	3%	21%	11%	8%	–	--
P8b	29%	13%	3%	5%	11%	3%	13%	8%	16%

Note. “A”: Algorithmic, “E” Efficient, “M” Messy, “I” Incomplete, “II” Incorrect strategies -Incorrect answer, “IC” Incorrect strategies-Correct answer, “N1” unsuccessful attempts, and “N2” correct guesses. P followed by a number denotes the problem number, “0” Missing problem solutions. P3b was canceled during the analysis of the results because students solved it as part of P3a.

Correlation between students’ conceptual understanding scores and their ability to solve problems correctly

There was a moderate to strong positive correlation (Pearson’s r=0.67, a <0.01 level) between students’ conceptual understanding scores and their ability to solve problems correctly even when using algorithmic solutions (Table 5).

Conceptual Understanding, Learning Approach and Problem solving strategies

The results showed the following regarding conceptual understanding, learning approach and problem solving strategies. These results are based on Tables 4 and 5. Table 4 presents a summary of students' conceptual understanding, learning approaches, and problem solving strategies from the analysis of the LAQ, the Stoichiometry Test, and the unstructured interviews. Table 5 presents students' problem solving strategies and their conceptual understanding scores.

1. Students with less conceptual understanding used more incorrect strategies and skipped more problems than those with more conceptual understanding. Students' misunderstandings seemed to impede their ability to construct correct solutions. This can be seen by looking across SCU - PCU - NCU for each learning approach in Table 4.

2. In general, students of different conceptual understanding levels tried to employ algorithmic strategies from memory to solve the test problems. Students with more conceptual understanding could use correctly the class-learned procedures more than those with less conceptual understanding. There was a positive correlation (Pearson's r=0.67, a <0.01 level) between students' conceptual understanding scores and their ability to solve problems correctly even when using algorithmic solutions (Table 5). Whereas students with less conceptual understanding, who solved problems algorithmically, did that with inadequate understanding of the concepts required (See Table 4).

3. The less conceptual thinkers often used algorithmic strategies and efficient strategies only for the typical and straightforward problems, but showed in the interview no conceptual understanding of the concepts required. They also skipped the more difficult and conceptual problems like P2b, P4, P5, P6b, P7a, P8b or solved them incorrectly; whereas the

more conceptual thinkers could solve more problems, typical as well as conceptual as shown in Table 4.

4. In the interview, students with more conceptual understanding were generally more able to argue conceptually than those with less conceptual understanding. In general, students with more conceptual understanding were able to correct the mistakes which they made in the test; whereas, those with less conceptual understanding were, most often, not able to do that as evident from examining MLA, ILA, and RLA in Table 4.

5. The learning approach, as measured by the LAQ, was not associated with conceptual understanding; the Pearson correlation r for the learning approach and the conceptual understanding was very low and statistically not significant $r = 0.18$, $\alpha > 0.05$. Also, no patterns could be found in the problem solving strategies used by students with different learning approaches (Table 4).

6. Students were more successful at solving the more straightforward and simple problems than the more complex and conceptual problems (Table 3).

Table 4

Conceptual understanding, learning approaches, and problem solving strategies from the analysis of the Approach to Studying Inventory, the stoichiometry test, and the unstructured interviews

	Sound Conceptual Understanding	**Partial Conceptual Understanding**	**No Conceptual Understanding**
Meaningful learning approach	S_{18} av: 83/100, cu: 8/10 - algorithmic 11, efficient 4, incorrect strategy-incorrect answer 2 -preferred his own method but followed the teacher's - had sound conceptual understanding as evident from both: the test and the interview __________________________ S_{12} av: 79/100, cu: 7/10 - algorithmic 9, efficient 3, incorrect strategy-incorrect answer 4, missing 1 - followed the teacher's method although he thought that his method was more appropriate -was bound to the format of typical stoichiometry problems - misunderstandings from test and interview: limiting reagent, conservation of mass, and molar quantities. - contradicted himself	S_{40} av: 81/100, cu: 5/10 - algorithmic 9, efficient 4, incorrect strategy-incorrect answer 4 -in the interview: corrected some mistakes and confirmed some others - misunderstandings from the test and the interview: molar volume at STP, conservation of mass, and significance of coefficients in the chemical equation _____________________________ S_{17} av:73/100, cu: 5/10 - algorithmic 6, efficient 4, incorrect strategy-incorrect answer 3, missing 2, incorrect strategy-correct answer 1, and no strategy 1 - algorithmic strategies were for the typical problems - in the interview: corrected some mistakes - misunderstandings: limiting reagent and coefficients in the chemical equation	S_{16} av: 71/100, cu: 4/10 - missing 1, algorithmic 5, efficient 3, incorrect strategy-incorrect answer 6, incorrect strategy-correct answer 2 - algorithmic strategies were for the typical problems of the test - misunderstandings: coefficients in the chemical equation, limiting reagent, and the mole.

	Sound Conceptual Understanding	**Partial Conceptual Understanding**	**No Conceptual Understanding**
Intermediate Learning Approach	S_{26} av:81/100, cu: 9/10 -algorithmic 10, efficient 5, incorrect strategy-incorrect answer 1, messy 1 - corrected mistakes during the interview -had sound conceptual understanding as evident from the test and the interview __________________________ S_{34} av:84/100, cu: 7/10 - algorithmic 6, efficient 5, incorrect strategy-incorrect answer 5, incorrect strategy-correct answer 1 - preferred and used his method although the teacher's was simple - in the interview: corrected some mistakes and confirmed some others - did not know UNDER what conditions a formula can be used - misunderstandings from the test and the interview: limiting reagent and significance of coefficients in the chemical equation - contradicted himself sometimes	S_{15} av:68/100, cu: 6/10 - algorithmic 6, efficient 2, incorrect strategy-incorrect answer 2, incorrect strategy-correct answer 2, no strategy 3, incomplete 1, and messy 1 - algorithmic and efficient strategies were for the typical problems in the test - bound to the format of typical stoichiometry problems - inconsistent in arguments - in the interview: corrected some mistakes and confirmed some others -misunderstandings from the test and the interview: conservation of matter, molar volume, molar volume at STP, and limiting reagent	S_4 av: 68/100, cu: 3/10 - no strategy 1, algorithmic 4, efficient 2, incorrect strategy-incorrect answer 9, incorrect strategy-correct answer 1 - algorithmic and efficient strategies were for the typical problems of the test - misunderstandings: coefficients in the chemical equation, molar volume at STP, and limiting reagents __________________________ S_{27} av: 69/100, cu: 2/10 - algorithmic 6, efficient 3, incorrect strategy-incorrect answer 6, incorrect strategy-correct answer 2 - preferred to solve problems which were exact copies of those solved in class - efficient and algorithmic strategies were not based on conceptual understanding - misunderstandings: coefficients in the chemical equation, molar volume, molar volume at STP, conservation of mass, and limiting reagents
	SCU	**PCU**	**NCU**

Rote Learning Approach	S_{24} av:91/100, sc: 9/10 -algorithmic 13, efficient 1, incorrect strategy-incorrect answer 2, messy 1 - tried to use all the given to solve a problem - in the interview: corrected his mistakes ____________________________ S_{28} av:74/100, cu:7/10 - algorithmic 8, efficient 4, incorrect strategy-incorrect answer 4 - formulas were important to him - had sound conceptual understanding as evident from test and interview - misunderstandings from test and interview: molar quantities	S_{33} av: 73/100, cu: 5/10 - missing 1, algorithmic 10, efficient 1, incorrect strategy-incorrect answer 4, incomplete 1 - algorithmic and efficient strategies were not based on conceptual understanding - misunderstandings: coefficient in the chemical equation, limiting reagent, molar volume at STP, and molar quantities ____________________________ S_{31} av: 71/100, cu: 5/10 - no strategy 3, algorithmic 10, efficient 1, incorrect strategy-incorrect answer 2, incomplete 1 - efficient strategies were for the simplest problems of the test - from interview: algorithmic strategies were not based on adequate conceptual understanding - misunderstandings: molar quantities and limiting reagents.	S_{32} av: 61/100, cu: 3/10 - no strategy 3, algorithmic 9, efficient 1, incorrect strategy-incorrect answer 4 - used all the given sometimes and neglected the given other times to solve a problem - correct strategies were not based on conceptual understanding - misunderstandings: of the five concepts and principles ____________________________ S_{39}: av:61/100, cu: 3/10 - missing 1, algorithmic 5, efficient 3, incorrect strategy-incorrect answer 7, correct strategy-incorrect answer 1 - used incorrect formulas - misunderstandings: of the five concepts and principles

Note: "cu" denotes conceptual understanding, "av" denotes final year average in chemistry, S followed a number denot es the students' number.

Table 5

Number of Students' Problem Solving Strategies and their Conceptual Understanding Scores

Subject		Correct Strategy			Incomplete	Incorrect Strategy		No Strategy	Missing Solution
	CU	A	E	M	I	II	IC	N	0
S_{22}	0	1	_	_	_	7	1	3	5
S_{21}	1	2	_	_	_	4	_	9	2
S_{30}	2	8	1	_	1	5	2	_	_
S_{27}	2	6	3	_	_	6	2	_	_
S_{38}	2.5	4	_	_	_	7	1	3	2
S_{20}	2.5	6	1	_	_	5	1	3	1
S_{32}	3	9	1	_	_	4	_	3	_
S_{39}	3	5	3	_	_	7	1	_	1
S_{29}	3	5	4	_	2	5	1	_	_
S_{4}	3	4	2	_	_	9	1	1	_
S_{37}	3.75	5	2	1	_	7	_	2	_
S_{1}	3.75	7	_	_	1	4	1	1	3
S_{8}	4	10	_	_	1	4	2	_	_
S_{16}	4	5	3	_	_	6	2	_	1
S_{31}	5	10	1	_	1	2	_	3	_
S_{2}	5	10	1	_	1	5	_	_	_
S_{5}	5	3	3	_	_	2	1	5	3
S_{33}	5	10	1	_	1	4	_	_	1
S_{3}	5	12	1	_	1	3	_	_	_
S_{19}	5	8	3	_	_	2	_	_	4
S_{17}	5	6	4	_	_	3	1	1	2
S_{40}	5	9	4	_	_	3	_	_	_
S_{25}	6	7	3	1	1	4	_	1	_
S_{23}	6	12	_	_	1	3	_	_	1
S_{35}	6	7	2	_	1	2	_	3	2
S_{15}	6	6	2	1	1	2	2	3	_
S_{7}	6	9	2	_	1	3	_	1	1
S_{14}	6	10	2	_	1	2	_	1	1
S_{28}	7	8	4	_	1	4	_	_	_
S_{34}	7	6	5	_	_	5	1	_	_
S_{10}	7	11	4	_	_	2	_	_	_
S_{12}	7	9	3	_	_	4	_	_	1
S_{9}	7	11	2	_	2	2	_	_	_
S_{6}	8	8	2	1	1	3	1	_	1
S_{18}	8	11	4	_	_	2	_	_	_
S_{24}	9	13	1	1	_	2	_	_	_
S_{26}	9	10	5	1	_	1	_	_	_
S_{11}	9	10	7	_	_	_	_	_	_
Total		295	85	6	19	145	21	43	32
%		45.7	13.2	0.9	2.9	22.4	3.3	6.7	5.0

Note. "CU" Conceptual Understanding Score, "A" Algorithmic, "E" Efficient, "M" Messy, "I" Incomplete, "II" Incorrect strategies-Incorrect answer, "IC" Incorrect strategies-Correct answer, "N" No strategy, and "0" Missing problem solutions. The percentage was calculated out 646, the total number of problem solutions.

Discussion

Students in this study used a variety of problem-solving strategies. However, they resorted mostly to algorithmic problem solving - which may be viewed as a safe and sure way to the correct answer - even when they did not have adequate understanding of the relevant concepts. Moreover, not surprisingly, students performed better on the problems that could be solved by applying algorithmic strategies than on the ones that required conceptual understanding of chemistry concepts. Similar results were obtained by BouJaoude (1994),

Mason, Shell, and Crawley (1997), and Nakhleh and Mitchell (1993). Analyzing the test responses and the interviews showed that some students were writing down formulas and plugging in numbers from the problems without any appreciation of the chemical systems that the problems represented. For example, for problem P7b on the test, S_{32} used the formula $n_1/n_2 = V_1/V_2$ for solids. Moreover, he had no idea as to when such a formula could be used when asked about it in the interview.

Actually, for the short and straightforward problems students were certain to attain the correct answer by merely relying on algorithms, similar to the students in Stanger and Greenbowe's (1997) study. However, as problems became longer or more conceptual, blind use of algorithms rarely did students any good. Consequently, the strategies they used were messy, either because of irrelevant steps or because the steps merely rendered the solution longer. Concern for grades, as evident from the interviews, may make students write steps that had no connection to what the question asked in the hope that one of the steps may lead them to the correct solution.

Previous studies showed a positive relationship between meaningful learning approaches and achievement in science where achievement was defined as conceptual understanding or conceptual change (BouJaoude, 1992; BouJaoude & Giuliano, 1991; Broathen & Hewson, 1989; Cavallo, 1992; Chan & Bereiter, 1992; Lee & Anderson, 1993; Rukavina, 1991). The importance of meaningful learning in promoting conceptual understanding that in turn facilitates problem solving was stressed by Ausubel (1968), Bransford and Stein (1984), and Eylon and Linn (1988). In the present study the learning approach, as measured by the LAQ, did not correlate with conceptual understanding and no patterns were found in the problem solving strategies used by students with different learning approaches. There are several possible explanations for this finding. First, teachers in highly selective schools, like the one in which the study was conducted, give prominence to preparing students to sit for high stakes national exams, which for the most part require students to solve academic chemistry problems. For this purpose, these teachers provide students with extensive practice in solving stoichiometry problems of different kinds. Consequently, the fact that most students successfully used or attempted to use algorithms may have masked the effect of conceptual knowledge and led to this lack of correlations since algorithms do not necessarily require the depth of understanding envisioned in the meaningful approach to learning. Second, there is the possibility that the LAQ is not a valid measure of students learning approaches in chemistry, even though it is valid in other subject matter areas (Chan & Bereiter, 1992; Lee & Anderson, 1993; Rukavina, 1991). The abstract nature of chemistry, the necessity of understanding the relationships between micro and macro properties for an accurate understanding of chemical concepts, and the need to apply the difficult and abstract concepts to solve problems may make chemistry very complex and harder than other subjects, and consequently less comprehensible, even for students who try hard to understand meaningfully. Third, there is the possibility that students' use of a strategy depended upon the difficulty of the problem rather than on any other variable.

A positive relationship between conceptual understanding and successful problem solving was supported by research conducted by Harmon (1993) and Staver and Lumpe (1995) where inadequate understanding impeded problem solving ability. Also, Bransford and Stein (1984) regarded conceptual knowledge as the most significant determinant of successful problem solving. In the present study, the more conceptual thinkers were the more successful problem solvers. This is in agreement with what Camacho and Good (1989) found.

Also, the incorrect strategies used by students were mainly due to inadequate conceptual knowledge as was evident from both the test and the interview of S_{12} in P1c:

I: Does the molar volume of a certain compound change? STP conditions.

S12: Oh, depends how many moles you have. Say you have one mole of this substance, it'll be 22.4; but if you have two, it will be 44.8. It depends on the number of moles you have.

I: But how can you define molar volume?

S12: Molar volume…it is the number of moles. I wouldn't exactly give a definition because… I mean…I don't know by definition… I just apply it.

I: What about the molar mass?

S12: The molar mass as I think is the number of moles…and…it's the number…it's the mass of something of example NH_3 in a certain number of moles.

I: Why did you use here molar mass of $2NH_3$?

S12: Because I used for 2NH3…because you have here $2NH_3$ you don't have one because you have $2NH_3$.

Niaz (1989,1995a, 1995b) found that good conceptual thinkers were good algorithmic problem solvers but good algorithmic problems solvers were not necessarily good conceptual thinkers. In the present study, the more conceptual thinkers were more successful than the less conceptual thinkers in responding to the test items and in answering the conceptual interview questions about the problems that were solved algorithmically in the test. The less conceptual thinkers tended to use only algorithms in solving problems, whereas the more conceptual thinkers employed their conceptual reasoning in addition to using algorithms; or, as Niaz (1995b) put it, they seemed to have constructed algorithms in a meaningful way. This might be why the more conceptual thinkers were more successful problem solvers and could use algorithms and formulas correctly.

Mason and Crawley (1994) found that the more conceptual thinkers solved problems with less number of steps than the less conceptual thinkers. In this study, this relationship was not evident for, as mentioned earlier, the general tendency of all the students was to follow algorithmic type -solutions. Moreover, the results of this study showed that students with different levels of conceptual understanding used efficient strategies. Important to note is that the students of less conceptual understanding who solved some problems efficiently may have seen similar shortcuts during private tutoring or previously solved problems in class. For example, a student (S27) who had solved problem 4 efficiently on the test was unable to explain how she reached the solution when asked to do so in the interview. S_{27} used the law of conservation of mass to solve P4 in one step only.

Excerpt from the test, P4:

$2CO_g + O_{2g}$ ® $2CO_{2g}$ *at STP*

2 moles 1 mole ® 2 moles

5g + 13g ® mass

The total mass of the contents of the container at the end of a reaction should be the same as the sum of the products at the beginning because in a chemical reaction, the mass of products is equal to mass of reactants, it doesn't change.

To find the mass of $2CO_2$*, we can do this: The number of moles is two moles and the m.mass = 56g*

n = mass/m.mass 2 = mass/56 mass = 112g.

To prove it is the same as on the other side, we will find that the addition of the masses of the other side will be 112g. In this problem we have the additions of reactants will be 18g, so the mass of the contents of the container at the end of the reaction will be also 18 grams.

S_{27} did not seem to understand what she wrote. The interview showed that she thought that all the 18 grams were carbon dioxide. Moreover, she said that her weakness stemmed from the difficulty she had with the mole concept. Moreover, she indicated that she preferred to solve problems that were similar to the ones solved in class.

S_{27}: I don't know what I did here ... I say the addition of reactants will be 18, so the mass of the contents of the container at the end will also be 18. I don't know why I got this, and I wrote this.

I: What will be these 18 grams?

S_{27}: The mass of $2CO_2$.

…

S_{27}: Ya, so I think I haven't understood everything in chemistry.

I: Why did you think that you didn't understand?

S_{27}: Well, the mole was very complicated at first, the mole as the mole, but then, when you…you understand the mole, and we got to stoichiometry too, you know we have to use the equations and everything. That's why it got really complicated, then even the moles, you know, it's .. it's if you understand one problem, when it comes to another one, you don't know, you may understand it when you saw how to do it. But when you come to another one, you don't know how to do it again unless it's, maybe, the photocopy, you know, that's something the exact copy of.

Many of the correct strategies, mainly the algorithmic ones, which appeared when solving the problems on the stoichiometry test were based on inadequate conceptual understanding as revealed from the interview questions that were mainly conceptual. Similar results were obtained by Lythcott (1990), Nakhleh (1993), Nakhleh and Mitchell (1993), Niaz (1995), Pickering (1990), and Sawrey (1990). Both concept learning and rule learning are prerequisites for problem solving (Till, Bersoff, & Dolly, 1976). Hayes (1981) highlighted the importance of procedural knowledge gained from experience. In this study, sound conceptual thinkers, even though they were the more successful problem solvers, made several mistakes in solving some of the problems. This may be due to insufficient practice of the "right type" in solving stoichiometry problems, which may have resulted in insufficient procedural knowledge or lack of reflective thinking and metacognitive strategies (Shaibu, 1992; Harmon, 1993).

Many of the results of this study agree with what Schmidt (1988, 1990, 1994, 1997) found about the incorrect procedures used when the relationships between mole, volume, mass, and molar quantities were used. Also, several misunderstandings about stoichiometry were identified by previous research such as those about the limiting reagent, the mole concept, stoichiometry in the chemical equation, and balancing of chemical equations (Huddle & Pillay, 1996; Staver & Lumpe, 1995; Tullberg , Strömdahl, & Lybeck, 1994). These findings across studies and in different cultural contexts (Germany, Lebanon, and the USA) point to the need for international collaboration among education professionals to find ways to improve the teaching and learning of chemistry.

Implications

The results of this study highlight the necessity of conceptual understanding and efficient and meaningful problem solving strategies for success in solving problems in chemistry. If science education aims to prepare students who can think conceptually, solve traditional as well as novel problems, work efficiently with confidence, use meaningful problem solving strategies, and are serious in pursuing the study of chemistry, then the focus should be on helping students understand rather than memorize chemistry content and use efficient strategies to solve chemistry problems. In addition, the nature of assessment used in schools and in national examinations should change. Rather than focusing on algorithmic problems, educators should include both numerical and conceptual real problems as described by Hayes (1981). Students and teachers focus on the things that usually appear on tests because of the perceived importance of these tests. Subjective tests or multiple-choice tests written properly are indispensable in assessing what students learn. Through these types of tests, teachers can understand students' thinking and problem-solving strategies and hence be more empowered to help their students improve their problem solving strategies and even develop some more efficient ones.

The largest numbers of students in this study were those with partial conceptual understanding. Moreover, some students were confused when using simple formulas - such as those for finding the molar mass, number of moles, and limiting reagent - most probably because these formulas were memorized rather than understood. Consequently, emphasis needs to be placed on making sure that students understand concepts as well as the conceptual foundations for formulas, students need to be meaningful rather than rote learners. For example, consider the calculation of the molar mass of ammonia in a given chemistry problem. The student should understand that: a) the discrete molecules of ammonia are NH_3, b) the molar mass of ammonia is the mass of the amount that contains Avogadro's number of particles, defined as the mole, c) one mole of ammonia contains one mole of nitrogen atoms and three moles of hydrogen atoms, d) the mass of one mole of an atom is equal to the atomic mass in grams which is actually the mass of the amount that contains Avogadro's number of particles, and e) the above statements are independent of the stoichiometry of ammonia in the chemical equation. It is less probable that a student makes mistakes in finding the molar mass if this concept is adequately understood. Because of the complexity of the issue, teachers may need to spend more time to explain concepts and formulas and ensure students' adequate understanding before starting to solve problems.

It seems that instruction, in general, emphasizes algorithmic problem solving at the expense of conceptual understanding and meaningful problem solving. However, research has shown that more emphasis should be dedicated to the concepts upon which problems are based. Furthermore, because of the relationships between students' classroom experiences, the learning approaches they develop, and learning outcomes (Ramsden, 1995; Ramsden, Martin, & Bowden, 1989) it is advisable for chemistry teachers to choose instructional approaches and classroom structures that encourage students to develop meaningful learning approaches and possibly more coherent conceptual understandings. Student-centered approaches such as discussion and cooperative learning may be useful in this respect (Nakhleh, Lowrey, & Mitchell, 1996; Phelps, 1996). Students should be convinced of the importance of conceptual understanding especially that Phelps (1996) found that instructional innovations face strong resistance at the beginning because students are used to and happy with numerical algorithmic problem solving.

Additionally, some problems (such as problem four) could be solved by at least two correct strategies. The first strategy takes longer because it includes finding the limiting reagent, the mass of carbon dioxide, the mass of the excess, and the total mass at the end of the reaction. The second strategy makes use of the concept of conservation of mass and only requires finding the total masses of reactants. The fact that there are two paths to the solution of the same problem directs attention to the efficiency and the meaningfulness of these solutions. It may be that the majority of students' self-confidence needs to be nurtured to help them solve problems in ways that are different and more efficient than those used in class. Teachers can help students appreciate the conceptual solutions and shortcuts by presenting and discussing several solutions for the same problem while, concurrently, emphasizing the importance of time during testing and in real life.

Encouraging conceptual understanding and problem solving in chemistry requires that the curriculum be redefined in terms of content and context. In addition, it requires more research on the complex relationships between students' approaches to learning and problem solving in chemistry because of the possible close association between content and learning approach (Ramsden, Martin, & Bowden, 1989). The content of the curriculum might be more useful if regarded as a vehicle to foster and improve students' thinking rather than a quantity of content to be memorized. To accomplish this, the content should be less, more in depth, and presented in a context from which the student can derive meaning and significance of chemistry, such as everyday life situations, environmental issues, and industrial processes.

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Appendix

STOICHIOMETRY TEST

Name: _______________School: _____________________Class: ________ Date:_____

Please explain how you solve each of the following problems. Write all the steps, and give reasons for the method you use. Do not forget to write the units.

1. Use the following equation: $N_{2(g)} + 3H_{2(g)} \rightarrow 2NH_{3(g)}$ at STP conditions

Atomic masses, N : 14; H : 1; parts a, b, and c are related to each other.

i) If 2.0 moles of nitrogen gas react completely, how many moles of ammonia will be produced? Explain.

ii) What volume does the ammonia produced in part a occupy at STP? Explain.

iii) Find the molar volume and the molar mass of ammonia.

2. Use the following equation: $2H_{2(g)} + O_{2(g)} \rightarrow 2H_2O_{(l)}$ at STP

Atomic masses, H : 1; O : 16; parts a and b are related to each other.

i) Find the number of moles of 3 L of hydrogen.

ii) 3 L of hydrogen react completely with enough oxygen, how do you find the volume of the water obtained. Write all steps and explain.

3. Use the following equation: $2CO_{(g)} + O_{2(g)} \rightarrow 2CO_{2(g)}$ at STP

Atomic masses, C : 12; O : 16; parts a, b, and c are related to each other.

i) Find the mass of carbon dioxide gas that will be produced from 22.4 L of oxygen gas. Write all the steps you use.

ii) Find the number of moles of the carbon dioxide produced in part a.

iii) Find the total mass of reactants used to produce the number of moles of carbon dioxide gas obtained in part b. Explain how you solve this part.

4. Use the follow ing equation: $2CO_{(g)} + O_{2(g)} \rightarrow 2CO_{2(g)}$ at STP

Atomic masses, C : 12; O : 16

In a closed container a scientist reacted 5 g of carbon monoxide gas and 13g of oxygen gas to produce carbon dioxide, what is the total mass of the contents of the container at the end of the reaction.

5. Use the following equation: $N_{2(g)} + 3H_{2(g)} \rightarrow 2NH_{3(g)}$ at STP

Atomic masses, N : 14; H : 1

i) If one liter of nitrogen gas reacts completely, can we say that 2 L of ammonia will be produced? Why? Explain.

ii) If one gram of nitrogen gas reacts completely, 2 grams of ammonia gas will be produced? Is this a correct statement? Explain your answer.

6. Use the following equation: $CH_{4g} + 2O_{2(g)} \rightarrow CO_{2(g)} + 2H_2O_{(l)}$ at STP

Density of O_2 at STP is 1.43 g/l

Atomic masses, C :12; H : 1; O : 16

i) Find the volume of methane gas needed to react completely with 2L of oxygen gas.

ii) If you have three containers:

- Container 1: Two moles of methane reacting with 4 moles of oxygen.
- Container 2: One mole of methane reacting with 4 moles of oxygen.
- Container 3: Four moles of methane reacting with 2 moles of oxygen

At the end of the reactions, in which container would you find the smallest total number of moles of all the gases present?

7. Use the following equation: $CaCO_{3(S)} + 2HCl_{(aq)} \rightarrow CO_{2(g)} + CaCl_{2(aq)} + H_2O$ at STP

Atomic masses, Ca : 40; C : 12; O : 16; H : 1; Cl : 35.5

i) If 14 grams of calcium carbonate react with 0.2 moles of hydrochloric acid, which reactant do you use in your calculations to find the mass of calcium chloride produced? and why?

ii) If 11.2 g of calcium carbonate react with 3 moles of hydrochloric acid, find the volume of carbon dioxide produced. Explain.

8. Use the following equation: $N_{2(g)} + 3H_{2(g)} \rightarrow 2NH_{3(g)}$ at STP

Atomic masses, N : 14; H : 1;

i) A scientist reacted 14 g of nitrogen gas and 4 g of hydrogen gas. How many grams of ammonia gas were produced? Write all steps and explain.

ii) If this scientist needed 25.5 g of ammonia gas with no excess of either reactants left. How many grams of each of hydrogenand nitrogen should he add to the 14 grams of nitrogen and 4 grams of hydrogen to obtain 25.5 grams of ammonia with no excess reactants left? Write all steps and explain.