University Students' Common Mistakes During Algorithmic Problem Solving in General Chemistry

Haluk ÖZMEN
Fatih Faculty of Education, Trabzon University, Akçaabat-Trabzon, Türkiye
E-mail: hozmen61@hotmail.com

Alipaşa Ayas
Faculty of Education, Bilkent University, Ankara, Türkiye
E-mail: alipasaayas@yahoo.com

Abstract
Algorithmic problem solving is accepted as the process of application of knowledge to novel situation and is an integral part of most science courses. It is known that students are not very successful in solving chemistry problems. In this study, the students' mistakes and difficulties while solving general chemistry problems were investigated. The study sample consists of 80 students who were enrolled in a chemistry course taught at the first year of university. To collect data a test consists of four problems was developed and implemented to 80 university chemistry students. The results of the study show that many of the students; had lack of prior knowledge, had lack of knowledge of mathematical procedures and these affected correct solutions of the problem, did not use the necessary units with appropriate exchanges, had difficulties to connect the topic with the problem and had not gained studying habits, as necessary.
Keywords: General chemistry, Problem solving, Students' difficulties
DOI: 10.7176/DCS/13-1-05
Publication date: January 31st 2023

Introduction
Science education generally aims achieving two goals. The first is the acquisition of a body of organized knowledge in a particular domain, and the second one is the ability to solve algorithmic problems in that domain (Duschl, Schweingruber & Shouse, 2007; Lee et al., 2001; Stomovlasis & Tsaparlis, 2000). Algorithmic problem solving is accepted as the process of application of knowledge to novel situation. Reid and Yang (2002) define the algorithmic problem as "*an algorithmic problem is a problem where all of the required data are provided, the methods of solution are familiar, and the goal is clearly stated*" and algorithmic problems are considered at a lower-level difficulty (Mensah & Morabe, 2018). On the other hand, there are increasing body of studies to remark that problem solving is a process promoting students' engagement in science practices beyond the rote memorization and simple algorithmic processing (Laverty et al., 2016; Stove & Cooper, 2017; Underwood et al., 2018). Although the problem solving is an integral part of most science courses, when they come across abstract science concepts students have difficulties to understand and apply them in algorithmic problems. Cardellini (2006) states that problem solving is something more than placing the numbers into well-learned formulas. Literature phrases that students must consider relevant features, ignore irrelevant features, and determine and use suitable problem-solving approaches to solve a problem successfully (Rodriguez et al., 2019). This process depends on many factors such as defining the problem correctly, focusing the problem, individual's skills of dealing with the problem (Dincol Ozgur, Temel & Yilmaz, 2012) and related to creativity, deliberation, and formal information. On the other hand, Solaz-Portales and Sanjose-Lopez (2009) states that there are many cognitive variables associated with students' problem-solving performance in science, such as mental capacity, field dependence and field independence, and the mobile/fixed cognitive style. However, studies assessing students' performance in problem solving show that students as well as teachers face many difficulties when they attempt to solve problems (Chen, Wilson & Lin, 2019). Based on this in academic domain, it is generally complained that students are poor algorithmic problem solvers. This point out that problem solving is very context dependent (Johnstone, 2001).

Algorithmic problem-solving occupy an important place in chemistry curriculum and has been regarded as a valuable assessment tool by educators (Salta & Tzougraki, 2011). Bennett (2004) reports that the types of problems in examinations or assessments in chemistry are largely algorithmic and this causes recall of algorithms and applications of the problem to those algorithms (Zoller & Tsaparlis, 1997). It is well known that students' performance on exams mostly depends on their problem-solving success and problem-solving performance is a critical component in science achievement (Lopez et al., 2014). Thus, only a meaningful understanding of concepts and clear conceptual connections between them can lead to the desired behavior in problem solving. In addition, Ekpete (2002) states that students must have both conceptual scientific and procedural knowledge to solve chemistry problems in an acceptable manner. And Clair-Thompson, Overton, and

Bugler (2012) states that there is no given data and ill-defined goals for the open-ended questions and a need for the participants to use unfamiliar methods. On the other hand, literature report that algorithmic problem solving is constrained by both participants' mental capacity (Danili & Reid, 2004; Tsaparlis, 2005) and mathematical processing skills (Gultepe, Celik & Kılıc, 2013), and these effect the quality of problem-solving skills (Mensah & Morabe, 2018).

Algorithmic problem solving which is critical feature for some of the highly quantitative chemistry topics such as chemical equilibrium, gas chemistry, electrochemistry, chemical kinetics, conservation of matter, solutions, balancing chemical reactions and stoichiometry, etc is based on understanding of the concepts and the rules interrelating them. Results of the research show that students often have difficulties in solving abstract and/or complicated chemistry problems in such concepts (Cheung, 2011; Cheung, Ma & Yang, 2009; Davidowitz, Chittleborough & Murray, 2010; Sanger, Vaughn & Binkley, 2013). This shows the deficiencies of the students in learning chemistry concepts effectively. In another words, solving chemistry problems also requires a good knowledge of chemistry (Frazer, 1982). It has been found that major obstacle to solving problems in chemistry are lack of understanding of chemical concepts and the blind reliance on algorithmic methods. Therefore, strategies for learning underlying concepts better will result in improving students' problem-solving ability (Gabel & Sherwood, 1984). For this reason, it is important to investigate the various problem-solving ways used by students and to determine students' mistakes, focusing on the nature of different problem-solving approaches and their role in helping the student to improve problem solving ability (Rodrigez et al., 2019). Because the students have difficulties in problem solving, teachers seek alternative ways of presenting problems to enable students to solve them more accurately. On the other hand, there are remarkable literature attempting to improve problem solving with specific problem-solving models (Bodner, 2015). These literatures show that a great majority of students do not understand underlying chemistry concepts which are used in solving chemistry problems or unable to apply their conceptual knowledge in problem solving. As indicated in some of the above literature, many of the students used memorized facts to solve problems and followed algorithmic methods in their solution rather than conceptual understanding (Lee, Goh & Chia, 1996).

Chemical reactions and stoichiometry are basic concepts in chemistry curricula. Understanding these concepts properly is vital for solving chemistry problems. It may be very difficult to solve the problems for students without understanding these concepts (Chandrasegaran, Treagust & Mocerino, 2007; Davidowitz, Chittleborough & Murray, 2010). For example, chemistry equation is the basic concept for solving various chemistry problems. A chemical equation summarizes the net changes in a reaction, but does not show details such as the mechanism, the spectator species or the reagent in excess and does not represent the submicroscopic nature of the reacting components (Davidowitz, Chittleborough & Murray, 2010). And the chemical equation is very important for reaction stoichiometry and has been identified as a difficult topic for learners (Fach, de Boer & Parchmann, 2007). In addition, one of the most basic concepts in chemistry is stoichiometry which requires to understand the qualitative and quantitative aspects of chemical phenomena as well as to solve various chemistry problems at different levels (Sunyono, Yuanita & Ibrahim, 2015). A whole understanding of stoichiometry requires more than the ability to follow an algorithm (Ben-Zvi, Eylon & Silberstein, 1988), since stoichiometric coefficients represent more than a simple mathematical method for balancing equations (Davidowitz, Chittleborough & Murray, 2010). Novice students may see balancing equations as the application of some basic rules (Laugier & Dumon, 2004) and may be able to use algorithms to solve problems in stoichiometry without understanding the transformations during the reaction (Papaphotis & Tsaparlis, 2008). But it is very important that solving problems involving chemical equations and stoichiometry requires both applying rules and understanding the concepts that give the rules meaning (Huddle & Pillay, 1996; Davidowitz, Chittleborough & Murray, 2010).

Based on the explanations above, we authors know that algorithmic problems are largely used for teachers, educators, and academics including us to measure students' academic achievement in chemistry classrooms. But we also believe that determining students' mistakes and difficulties in solving algorithmic problems is as important as measuring their academic achievement. This belief leads us to determine students' mistakes and difficulties while solving the problems because we think that improving the algorithmic problem-solving skills of students is primarily based on determining their problems, difficulties, misunderstandings, and mistakes encountered during this process. That the instructors become aware of the students' mistakes give them opportunity to take students attention on their mistakes, to understand students' thinking and reasoning, and to correct them scientifically correct ones. Based on this thought, it is aimed to investigate the students' mistakes in solving general chemistry problems in current study.

Methodology

The sample

The study involved 80 students who were enrolled in a general chemistry course taught at the first year of their education at the department of chemistry education in a public university in Türkiye. The students enrolled in the department have passed a nation-wide competitive university entrance examination done yearly among senior high school graduates (ages 17-18). The study sample was at the first year of their four-year program to become chemistry teachers for secondary schools (senior high schools).

The procedure

General chemistry is a four-credit course taken two consecutive terms as General Chemistry - I and General Chemistry - II. In these courses, students are given all the subjects covered in general chemistry, such as atomic and molecular structure, states of matter, chemical reactions, chemical equilibrium, bonding, chemistry of the elements, acids, bases, chemical kinetic, electrochemistry, oxidation-reduction, combustion, etc. Students are given open-ended and algorithmic problems to grasp the concepts at the end of each unit. Students are evaluated besides the end of unit test performance with two exams, one midterm and one final.

In this study, the data was collected by using a test which consists of four general chemistry problems that were specifically selected for a deeper investigation. The content validity of the test was guaranteed by asking a group consisting of nine experts (two chemistry education professor, four chemists with PhD degrees, and three chemistry educators). Twenty-five students who did not take part in the main study were asked to confirm the clarity and readability of the test.

The test was implemented to 80 students at the end of the second semester. The students' solutions were analyzed in detail and classified into correct, semi-correct, mistake and no response categories. After that the percentages of responses in each category were calculated. The categories are explained below briefly.

The correct category: If the students wrote the equation and balance it correctly in problem 1 and wrote and balance the equation and made mathematical calculations correctly in other problems, such answers were involved in this category.

The semi-correct category: If the students wrote the equation but not to balance it correctly in problem 1 and wrote and balanced equation correctly but made some mathematical mistakes in other problems, such answers were involved in this category.

Mistake category: If the students made mistakes in both writing and balancing the equations and making mathematical operations, such answers were involved in this category.

Results

The four problems selected for deeper investigation and students' mistakes are presented in the following paragraphs and tables.

Problem 1.

a. *Wolfram (IV) oxide is treated in aqueous acidic solution with cyanat to give octacyanowolfram (IV) ion and oxygen.*

b. *Chrome (III) iodur is treated in aqueous basic solution with chloride to give chromate, iodate, and the others.*

Please write chemical equations for (a) and (b).

Students' answers to the problem 1 are presented in Table 1.

Table 1. Students' answers to the problem 1

Categories (N = 80)	a		b	
	Number of students	%	Number of students	%
Correct answer	1	1.25	9	11.25
Semi – correct answer	3	3.75	8	10.00
Mistake	47	58.75	42	52.50
No response	29	36.25	21	26.25

As seen from the table 1, 29 of the students (36.25%) did not give any response to part *a,* and 21 (26.25%) to part *b* section of the question. In a detailed investigation it was found that 19 of the students did not respond to both part *a* and part *b*. It was noticed that those who gave wrong answers made mistakes in writing formulae of ions and/or equations. Most of the students' mistakes were like not finding the correct reductant and oxidant atoms in the formulae, and their correct charges, and not balancing the charge in both side of the equation and not balancing the number of atoms for the law of conservation of mass. When it was investigated the correct answers' ratio it was shown that while 1 of the students (1.25%) gave correct answer to part *a,* 9 of the students (11.25%) gave correct answer to part *b*. However, the students must identify the products in addition to the balancing the equation in part *b,* all the products have been identified in part *a.* This was an interesting result. Some of the common students' mistakes for the problem 1 are given in Table 2.

Table 2. Some of the students' mistakes for the problem 1

Mistakes	Number of students	%
$W_4(CN)_8$	10	12.50
CN_7W^{+4}	1	1.25
WCN_8^{-3}	1	1.25
$W(CN)_4$	4	5.00
CN_8W_4	7	8.75
WCN_8^{+4}	8	10.00
CN_8W^{-4}	4	5.00
SCN_8W_4	2	2.50
IO_4^-	15	18.75
IO_2^-	8	10.00

Correct answer: W $(CN)_8^{-4}$ for *a* and IO_3^-, CrO_4^- for *b*

Problem 2.

The concentrations of calcium ion (Ca^{+2}), phosphate ion (PO_4^{-3}) and hydroxide ion (OH^-) in normal blood plasma are 2.5x10^{-3} M, 2.2x10^{-3} M and 6.3x10^{-7} M, respectively. Calculate the Q value and compare it with solubility product (K_{sp}) value. Solubility product [(K_{sp}) for hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$) is 1.1x10^{-111}].

Students' answers to the problem 2 are given in Table 3.

Table 3. Students' answers to the problem 2

Categories	Number of students	%
Correct answer	22	27.50
Semi-correct answer	39	48.75
Mistake	10	12.50
No response	9	11.25

As seen from the table 3, most of the students solved the problem either correctly or semi–correctly. It was seen that majority of the students who gave semi-correct answers could not do mathematical calculations about exponential numbers. In addition, 6 of these students made mistakes in mathematical operations although they wrote both equation and Q statement correctly. Also, 4 of the students could not compare Q value with solubility product (K_{sp}). The students who gave wrong answers made mistakes in writing both equation and the statement of the Q value. Although the problem involved chemical equilibrium and a double headed arrow should be used to reflect this kind of chemistry, most of the students used a single headed arrow which implied that the reactions indicated proceed to completion. Some of the common students' mistakes for the problem 2 are given in Table 4.

Table 4. Some of the students' mistakes for the problem 2

Mistakes	Number of students	%
$Ca_{10}(PO_4)_6(OH)_2 \rightarrow 10Ca^{+2} + 6PO_4^{-3} + H_2O$	1	1.25
$1/2\ Ca_{10}(PO_4)_6(OH)_2 \rightarrow 5Ca^{+2} + 3PO_4^{-3} + OH^-$	2	2.50
$Q = [Ca^{+2}][PO_4^{-3}][OH^-]$	2	2.50
$Q = [Ca^{+2}]^{10}[PO_4^{-3}]^6$	3	3.75
$Q = 10\ [Ca^{+2}]\ 6[PO_4^{-3}]\ 2[OH^-]$	1	1.25
$Q = \frac{[Ca^{+2}]^{10}[PO_4^{-3}]^6[OH^-]^2}{Ca_{10}(PO_4)_6(OH)_2}$	1	1.25

Correct answer: $Ca_{10}(PO_4)_6(OH)_2 \rightleftharpoons 10Ca^{+2} + 6PO_4^{-3} + 2OH^-$

$$Q = [Ca^{+2}]^{10}[PO_4^{-3}]^6[OH^-]^2$$

Problem 3.

The solubility of barium sulfate, $BaSO_4$, in water is 2.3 mg/L. Calculate the solubility of barium sulfate in pure water and 0.01 M sodium sulfate solution. The molecular weight for barium sulfate is 233g.

Students' answers to the problem 3 are given in Table 5.

Table 5. Students' answers to the problem 3

Categories	Number of students	%
Correct answer	23	28.75
Semi-correct answer	22	27.50
Mistake	29	36.25
No response	6	7.50

It was determined that all the students who gave the problem semi-correct answers made mistakes in mathematical operations. These students calculated the solubility of barium sulfate in 1-liter pure water, but they could not calculate it in 0.01 M sodium sulfate solution. Some of the students' failed to turn milligram to gram and did not use the units. Majority of the students who gave erroneous answers to the problem used the solubility value and they calculated solubility product; the others could not use the data provided at all. In addition, some of the students indicated ionization of sodium sulfate as equilibrium. Some of the common students' mistakes for the problem 3 are given in Table 6.

Table 6. Some of the students' mistakes for the problem 3

Mistakes	Number of students	%
$K_{sp} = 0.9x10^{-5}$ x 0.01	4	5.00
$K_{sp} = 0.9x10^{-5}$ x 0.01x $(0.9x10^{-5} + 0.01)$	10	12.50
$K_{sp} = 0.01$ x 0.01	1	1.25
$S = \sqrt{9.8 \text{ x } 0.01}$	1	1.25
$S = [2Na^+]^2[SO_4^{-2}]$	3	3.75
$Ksp = 1.0x10^{-5}$ x 0.02 = 10^{-7} $S = \sqrt{10^{-7}}$	1	1.25
$Na_2SO_{4\,(s)} \rightleftharpoons 2Na^+_{(aq)} + SO_4^{-2}{}_{(aq)}$	12	15.00
$S = \dfrac{[Na^+][SO_4^{-2}]}{[BaSO_4]}$	1	1.25
$S = \dfrac{2.3}{233}$	13	16.25
$S = \dfrac{2.3\,/233}{1}$	10	12.50

Correct answer:

$$[Ba^{+2}] = [SO_4^{-2}] = S = \frac{2.3x10^{-3} \text{ g} / 233 \text{ g} / \text{mole}}{1 \text{ Liter}} = 1.0x10^{-5} \text{ mole/L}$$

$$BaSO_{4\,(s)} \rightleftharpoons Ba^{+2}{}_{(aq)} + SO_4^{-2}{}_{(aq)} \qquad x = K_{sp} / 0.01 = 1.0x10^{-10} / 0.01$$

$$x \qquad x + 0.01 \qquad x = 1.0x10^{-12}$$

Problem 4.

A mixture of NaF and KF weighted 0.7464 grams is dissolved in water, then it is treated with enough $CaCl_2$ and a solid weighted 0.6018 grams precipitated from the solution.

a. *What is the percentage of KF in the mixture?*

b. *What is the minimum and maximum mass of precipitate obtained from any mixture weighted 0.7462 grams? (Na: 23g, K: 39g, Ca: 40g and F: 19g)*

Students' answers to the problem 4 are given in Table 7.

Table 7. Students' answers to the problem 4

Categories	a		b	
	Number of students	%	Number of students	%
Correct answer	25	31.25	20	25.00
Semi-correct answer	6	7.50	6	7.50
Mistakes	31	38.75	50	62.50
No response	5	6.25	4	5.00

In this question, it was determined that those who answered the first part of the question (a) indicated that the precipitate is NaCl - KCl or $CaCl_2$ or CaO rather than CaF_2. Although some students wrote and balanced equation, they ignored coefficients in calculations. Some students who gave semi-correct answers made mistakes in mathematical operations, and the others calculated molecular weights of compounds erroneously. Some of the common students' mistakes for the problem 4 are given in Table 8.

Table 8. Some of the students' mistakes for problem 4

Mistakes	Number of students	%
$\frac{84\ g\ NaF}{117\ g\ NaCl} \times X\ g\ NaCl + \frac{116\ g\ KF}{149\ g\ KCl} \times (0.6018 - x)\ g\ KCl = 0.7462\ g$	3	3.75
$\frac{W_{NaCl}}{W_{NaF}} \times X\ g + \frac{W_{KF}}{W_{NaF+KF}} \times (0.7462 - x)\ g = 0.7462\ g$	26	32.50
$\frac{W_{NaF}}{W_{NaF+KF}} \times X\ g + \frac{W_{KCl}}{W_{KF}} \times (0.7462 - x)\ g = 0.6018\ g$	1	1.25
$\frac{W_{CaF2}}{W_{NaF}} \times X\ g + \frac{W_{CaF2}}{W_{KF}} \times (0.7462 - x)\ g = 0.7462\ g$	10	12.50
$\frac{W_{NaF}}{100} = \frac{X}{0.7462}$, $\frac{W_{KF}}{100} = \frac{X}{0.7462}$	2	2.50
$\frac{W_{NaCl}}{W_{NaF}} \times 0.7462$, $\frac{W_{KCl}}{W_{KF}} \times 0.7462$	26	32.50
$\frac{W_{CaF2}}{W_{NaF}} \times 0.7462\ g\ NaF$, $\frac{W_{CaF2}}{W_{KF}} \times 0.7462\ g\ KF$	10	12.50
$\frac{W_{mixture}}{W_{precipitate}} \times 100$	5	6.25

Correct answer:

a. $$\frac{78\ g/mole\ CaF_2}{2 \times 42\ g/mole\ NaF} \times X\ g\ NaF + \frac{78\ g/mole\ CaF_2}{2 \times 58\ g/mole\ KF} \times (0.7462 - x)\ g\ KF = 0.6018\ g$$

b. $$\frac{W_{CaF2}}{2 \times W_{NaF}} \times 0.7462\ g\ NaF, \quad \frac{W_{CaF2|}}{2 \times W_{KF}} \times 0.7462\ g\ KF$$

In this study, the students' mistakes in solving general chemistry problems were investigated. To reach this aim, a test with four general chemistry questions was developed. The results of this study indicated that many of the students made mistakes during solving the problems.

Students' responses to problems are categorized as correct responses, semi-correct responses, and mistakes Another category is no response. Tables 1, 3, 5 and 7 reflected the students' responses to the problems. As seen from tables, the students gave correct answers to problems with a ratio of 12.50% for problem 1 (1.25% for part *a,* and 11.25% for part *b*), 27.50% for problem 2, 28.75% for problem 3 and 56.25% for problem 4 (31.25% for part *a,* and 25% for part *b*). Overall, these results are not pleasant. That means most of the students made mistakes in solving problems. Some of common students' mistakes are given in Tables 2, 4, 6 and 8. In summary, these are as follows:

In problem 1:

- to write formulas erroneously,

In problem 2:
- to write equation erroneously,
- to use a single headed arrow,
- to write Q statement erroneously,
- to make errors in mathematical operations with exponential numbers,

In problem 3:
- to make no unit conversation process as necessary,
- to use calculated solubility value instead of K_{sp},
- to write solubility product (K_{sp}) statement erroneously,

In problem 4:
- to write chemical equation for the problem erroneously,
- to ignore coefficient in calculations,
- to take mixture of NaCl – KCl as a precipitate instead of CaF_2.

In problem 1, the students made mistakes in writing the correct formula for ions and compounds, correct ion charges and the atoms' charges in compounds. This shows that the students have lack of knowledge of the topic. Also, some of the mistakes in problem solving can occur because the students were unable to remember the correct mathematical formula for the solution of the problem. Such kinds of mistakes were detected in the problems 2, 3 and 4.

The results obtained from the analysis of the responses to the problem 2 indicated that the students have lack of ability in terms of procedural knowledge in solving problems. The students had difficulties to carry out procedures especially with exponential numbers.

When we examine the students' answers for the problem 3, it was determined that the students faced difficulties in terms of understanding the given data, using, and exchanging the units. Therefore, they reached solution that was not correct or left the problem unsolved.

Examining responses given to the problem 4 showed that many of the students were unable to write the correct chemical equation. Those who wrote the equation correctly did not consider the mole numbers in calculations. This situation can be interpreted as that the student did not know the meaning of the mole numbers in the equations.

Another difficulty of the students was lack of the ability of doing mathematical operation. Although some of the students had required knowledge to solve the problems, they made mistakes in their mathematical operations and their solutions were wrong.

Discussion and Conclusion

Algorithmic problem-solving is important in chemistry because this activity is used for assessment of the student's success in all levels. This also makes important both determining problem-solving levels and strategies used and/or developed by students (Broman, Bernholt & Parchmann, 2018) and revealing students' difficulties and mistakes during the algorithmic problem-solving process. It is well-known that students' performances are high in solving algorithmic chemistry problems than the conceptual problems covering the same topics (Broman, Bernholt & Parchmann, 2018; Salta & Tzougraki, 2011). But this does not mean that students are very good at algorithmic problem-solving. As determined in this study, algorithmic problem-solving process also includes some problems with regards to students. First, concepts such as chemical equation, mole, chemical reaction and balancing, stoichiometry are very difficult, abstract, and problematic for the students. Such concepts may be very simple, obvious, and appear for expert chemists but they include much unfamiliar aspect or new information for a novice student (Davidovitz, Chittleborough & Murray, 2010). On the other hand, effectively learning of these concepts are prerequisite for many chemistry concepts such as chemical equilibrium, solutions, chemical kinetics, etc to learn and to solve the problems by the students.

The results of the study show that students made some mistakes to solve the problems. The most common students' mistakes are writing chemical formulas and equations for the problems erroneously and ignore coefficients in mathematical calculations. Chemical formulas and equations have a typical language, and this is very important. Literature report that some students have a full understanding of the different meanings of chemical symbols and coefficients, while others will simply attempt to balance the equation by trial and error (Davidovitz, Chittleborough & Murray, 2010). On the other hand, Marais and Jordaan (2000) investigated the mistakes in interpreting the symbols in a chemical reaction for students who may have difficulties in distinguishing the difference between coefficients and subscripts. They found that while 41.9% of the students was able to identify square brackets in [NO_2] as representing the molar concentration of NO_2, only 7.4% of them knew that $2NO_2$ referred to two moles of NO_2. This show that students have difficulties in interpreting symbols and symbolic nature of the chemistry. This is also related the stoichiometric nature of the chemical equations. Namely, students consider that coefficients and subscripts are different numbers, and their meaning is different from each other. Understanding this difference provides students to make stoichiometric calculations correctly.

Sholihah, Latisma and Efendi (2017) report that students must understand the stoichiometry concept to understand the chemical calculation material at the next level.

School learning still focuses mainly on lower-order cognitive skills such as rote memorization, recall, and algorithmic teaching with one single expected answer (Bennett, 2008; Broman & Parchmann, 2014; Overton, Potter & Leng, 2013; Sevian & Talanquer, 2014). Papaphotis and Tsaparlis (2008) report that algorithmic questions might be answered by employing only rote learning, and more generally, through lower-order cognitive skills. Also, traditional teaching and assessment practices requires algorithmic thinking and rote memorization of concepts, facts, or chemical formulas (Chen, Wilson & Lin, 2019). On the other hand, literature report that student difficulties, mistakes and failures have been attributed to rote memorization and misuse of chemical formula (Lin, Cheng & Lawrenz, 2000), or poor external representation and internal interpretation of a chemistry problem or phenomena (Matijasevic et al., 2016). Also, results of literature conclude that ability to apply a well-practised algorithm to solve problems does not signify conceptual understanding (Francisco et al., 2002; Mason, Shell & Crawley, 1997; Niaz & Robinson, 1992). On the contrary, conceptually literate students are more likely to be successful in solving well-practised algorithmic problems (Niaz, 1995). Students' ability to solve problems using algorithms without the reasoning and processing skills demonstrate a concomitant conceptual understanding (BouJaoude & Barakat, 2000; Sanger, 2005; Papaphotis & Tsaparlis, 2008). Therefore, instructor should give priority to teach conceptual context to the students. On the other hand, algorithmic problem solving is an important part of the chemistry curricula and students' difficulties and mistakes in this context are also an important issue that needs to be addressed. Teachers can only correct students' mistakes if they know them. So, it is important for teachers to analyze students' mistakes in detail to provide them with correct feedback. We try to make this in the present study and believe that if we draw chemistry teachers' attention to the students' mistakes, this may give them an opportunity to overcome the common learning difficulties. In addition, if the teacher realize that students cannot learn enough with existing methods, they try to look for new methods. Although it is not common for teachers to follow the current literature to be aware of new teaching methods is important. For example, Davidovitz, Chittleborough and Murray (2010) report on a pedagogical approach to the teaching of chemical equations introduced to first year university students with little previous chemical knowledge. In this approach, during the instruction period students had to interpret and construct diagrams of reactions at the submicro level and relate them to chemical equations at the symbolic level. The aim of this is improving students' conceptual understanding of chemical equations and stoichiometry. Results indicated that there was a consistent improvement in the abilities of students to answer stoichiometry questions correctly. That the teachers are aware of students' difficulties and cannot overcome them lead them to discover new ways to solve this problem.

Another reason found with the study context is that there is a high competition among secondary school graduates to enroll at universities. This competition pushes the students and secondary school teachers to only prepare students to the exam which is done yearly rather than concentrating on conceptual learning of chemistry at secondary level. This is true for other subjects as well. Therefore, the prior knowledge that the students should have gained from their secondary schooling lacks in chemistry as well as in other subjects. One of the possible solutions for this is to use a more comprehensive exam for university entrance based on not only procedural but also conceptual knowledge.

The reasoning is very important to learn conceptually and become a good problem solver. In some cases, during the problem-solving sections the students learn only procedural sides of problems and they memorize the procedure without learning the reason why we do such attempts in solving the problems. Therefore, the problem-solving process should be organized so that each student has taken their own responsibility in problem solving sections. They may develop their own way in solving the problem and construct their own meaning. As indicated by many constructivists, learning in this way is more quality (Osborne & Wittrock, 1983; Driver, Guesne & Tiberghien, 1985).

The study sample is very small to make generalization of the results. However, similar kinds of research should be carried out to find out more about students' problem-solving difficulties and mistakes in different topics of general chemistry as well as other areas of chemistry at different levels of education. In addition, in this study, it was aimed to detect students' mistakes in solving chemistry problems. Because the authors of this study did not take part in teaching General Chemistry-I and General Chemistry-II courses, the mental processes behind the students' mistakes and solutions could not be revealed in the study. Although determination of the students' mistakes in problem solving is important, it is necessary to identification of the students' mental processes and conceptual knowledge used in problem solving process. This is the only way to help students to overcome and/or correct their mistakes. In addition, conceptual understanding of chemistry by students and developing higher-order cognitive skills of them are also very important and teachers should be encouraged to choose and employ different methods to make students conceptually qualified.

Conflicts of interest
There are no conflicts to declare.
Author contributions
Co-author has substantially contributed to conducting the underlying research and drafting this manuscript.
Ethical approval
All the procedures performed in the study were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

References

Bennett, S.W. (2004). Assessment in chemistry and the role of examination. *University Chemistry Education*, *8*, 52-57.

Bennett, S.W. (2008). Problem solving: Can anybody do it? *Chemistry Education Research and Practice*, 9(1), 60-64.

Ben-Zvi, R., Eylon, B., & Silberstein, J. (1988). Theories, principles and laws. *Education in Chemistry*, 25, 89-92.

Bodner, G.M. (2015). *Research on problem solving in chemistry, in Garcia-Martinez J. and Serrano-Torregrosa E*., (ed.), Chemistry Education: Best Practices, Opportunities and Trends, Weinheim, Germany, Wiley-VCH Verlag GmbH & Co. KGaA, pp, 181-201.

BouJaoude, S., & Barakat, H. (2000). Secondary school students' difficulties with stoichiometry. *School Science Review,* 81(296), 91-98.

Broman, K., Bernholt, S., & Parchmann, I. (2018). Using model-based scaffolds to support students solving context-based chemistry problems. *International Journal of Science Education*, 40(10), 1176-1197.

Broman, K., & Parchmann, I. (2014). Students' application of chemical concepts when solving chemistry problems in different contexts. *Chemistry Education Research and Practice*, 15(4), 516-529.

Cardellini, L. (2006). Fostering creative problem solving in chemistry through group work. *Chemistry Education Research and Practice,* 7(2), 131-140.

Chandrasegaran, A.L., Treagust, D.F., & Mocerino, M. (2007). Enhancing students' use of multiple levels of representation to describe and explain chemical reactions. *School Science Review*, 88(325), 115.

Chen, Y.-C., Wilson, K., & Lin, H.-S. (2019). Identifying the challenging characteristics of systems thinking encountered by undergraduate students in chemistry problem-solving of gas laws. *Chemistry Education Research in Practice*, 20, 594-605.

Cheung, D. (2011). Using diagnostic assessment to help teachers understand the chemistry of the lead-acid battery. *Chemistry Education Research and Practice*, 12, 228-237.

Cheung, D., Ma, H.J., & Yang, J. (2009). Teachers' misconceptions about the effects of addition of more reactants or products on chemical equilibrium. *International Journal of Science and Mathematics Education*, 7, 1111-1133.

Clair-Thompson, H., Overton, T., & Bugler, M. (2012). Mental capacity and working memory in chemistry: algorithmic versus Mental capacity and working memory in chemistry: algorithmic versus. *Chemistry Education Research and Practice,* 13, 484-489.

Danili, E., & Reid, N. (2004). Some strategies to improve performance in school chemistry based on two cognitive factors. *Research in Science and Technological Education*, 22, 203-223.

Davidowitz, B., Chittleborough, G., & Murray, E. (2010). Student-generated submicro diagrams: A useful tool for teaching and learning chemical equations and stoichiometry. *Chemistry Education Research and Practice*, 11(3), 154-164

Dincol Ozgur, S., Temel, S., & Yilmaz, A. (2012). The effect of learning styles of preservice chemistry teachers on their perceptions of problem-solving skills and problem-solving achievements. *Procedia - Social and Behavioral Sciences,* 46, 1450-1454.

Driver, R., Guesne, E., & Tiberghien, A. (1985). *Children's ideas in science.* Open University Press, Milton Keynes.

Duschl, R.A., Schweingruber, H.A., & Shouse, A.W. (Eds.). (2007). Taking science to school: learning and teaching science in grades K-8. Washington: National Academies Press.

Ekpete, O.A. (2002). Enhancing understanding chemical arithmetic in learning of chemistry. *African Journal of Research in Education*, 2, 162-165.

Fach, M., de Boer, T., & Parchmann, I. (2007). Results of an interview study as basis for the development of stepped supporting tools for stoichiometric problems. *Chemical Education Research and Practice*, 8, 13-31.

Francisco, J.S., Nakhleh, M.B., Nurrenbern, S.C., & Miller, M.L. (2002). Assessing student understanding of general chemistry with concept mapping. *Journal of Chemical Education*, 79, 248-257.

Frazer, M.J. (1982). Nyholm lecture: solving chemical problems. *Chemical Society Review*, 11**,** 171-190.

Gabel, D., & Sherwood, R.D. (1984). Analyzing difficulties with mole concept tasks by using familiar analog tasks. *Journal of Research in Science Teaching,* 21, 843-851.

Gultepe, N., Celik, A.Y., & Kilic, Z. (2013). Exploring effects of high school students' mathematical processing skills and conceptual understanding of chemical concepts on algorithmic problem solving. *Australian Journal of Teacher Education*, 38(10), 106-122.

Huddle, A.P., & Pillay, A.E. (1996). An in-depth study of misconceptions in stoichiometry and chemical equilibrium at a South African University. *Journal of Research in Science Teaching*, 33, 65-77.

Johnstone, A.H. (2001). Can problem solving be taught? *University Chemistry Education,* 5, 69-73.

Laugier, A., & Dumon, A. (2004). The equation of reaction: a cluster of obstacles which are difficult to overcome. *Chemistry Education Research and Practice*, 5, 327-342

Laverty, et al. (2016). Characterizing college science assessments: The three-dimensional learning assessment protocol. *PLoS One*, 11(9), 1-21.

Lee, K.W., Goh, N.K., & Chia, L.S. (1996). Cognitive variables in problem solving in chemistry: A revisited study. *Science Education,* 80, 691-710.

Lee, K.W.L. et al. (2001). The predicting role of cognitive variables in problem solving in mole concept. *Chemistry Education: Research in Practice in Europe*, 2*,* 285-301.

Lin, H.S., Cheng, H.J., & Lawrenz, F. (2000). The assessment of students' and teachers' understanding of gas laws. *Journal of Chemical Education*, 77, 235-238.

Lopez, E.J. et al. (2014). Factors contributing to problem-solving performance in first-semester organic chemistry. *Journal of Chemical Education*, 91, 976-981.

Marais, P., & Jordaan, F. (2000). Are we taking symbolic language for granted? *Journal of Chemical Education*, 77, 1355-1357

Mason, S.D., Shell, D.F., & Crawley, F.E. (1997). Differences in problem solving by nonscience majors in introductory chemistry on paired algorithmic-conceptual problems. *Journal of Research in Science Teaching*, 34, 905-923.

Matijasevic, I. et al. (2016). Translation of P = kT into a pictorial external representation by high school seniors. *Chemistry Education Research and Practice*, 17, 656-674.

Mensah, A., & Morabe, O.N. (2018). Strategies used by grade 12 physical sciences students in solving chemical equilibrium problems. *African Journal of Research in Mathematics, Science and Technology Education,* 22(2), 174-185.

Niaz, M. (1995). Progressive transitions from algorithmic to conceptual understanding in student ability to solve chemistry problems: A Lakatosian interpretation. *Science Education,* 79, 19-36.

Niaz, M., & Robinson, W.R. (1992). From 'algorithmic mode' to 'conceptual Gestalt' in understanding the behavior of gases: an epistemological perspective. *Research in Science and Technology Education*, 10, 53-64.

Osborne, R.J., & Wittrock, M.C. (1983). Learning science: A generative process. *Science Education,* 67, 489-508.

Overton, T.L., Potter, N.M., & Leng, C. (2013). A study of approaches to solving open-ended problems in chemistry. *Chemistry Education Research and Practice*, 14(4), 468-475.

Papaphotis, G., & Tsaparlis, G. (2008). Conceptual versus algorithmic learning in high school chemistry: the case of basic quantum chemical concepts, Part 1, Statistical analysis of a quantitative study. *Chemistry Education Research and Practice*, 9, 323-331.

Reid, N., & Yang, M.J. (2002). Open-ended problem-solving in school chemistry: A preliminary investigation. *International Journal of Science Education*, 24(12), 1313-1332.

Rodriguez, J.G. et al. (2019). Productive features of problem solving in chemical kinetics: more than just algorithmic manipulation of variables. *Chemistry Education Research and Practice,* 20*,* 175-186.

Salta, K., & Tzougraki, C. (2011). Conceptual versus algorithmic problem-solving: focusing on problems dealing with conservation of matter in chemistry. *Research in Science Education*, 41(4), 587-609.

Sanger M.J. (2005). Evaluating students' conceptual understanding of balanced equations and stoichiometric ratios using a particulate drawing. *Journal of Chemical Education*, 82, 131-134.

Sanger, M.J., Vaughn, C.K., & Binkley, D.A. (2013). Concept learning versus problem solving: Evaluating a threat to the validity of a particulate gas law question. *Journal of Chemical Education*, 90, 700-709.

Sevian, H., & Talanquer, V. (2014). Rethinking chemistry: A learning progression on chemical thinking. *Chemistry Education Research and Practice*, 15(1), 10-23.

Sholihah, A.U., Latisma, Dj., & Efendi, J. (2017). Development of stoichiometry module based on problem solving for grade X of high school students. *International Journal of Research in Counseling and Education*, 1(1), 1-9.

Solaz-Portoles, J.J., & Sanjose-Lopez, V. (2009). Working memory in science problem solving: a review of research. *Revista Mexicana de Psicologia*, 26(1), 79-90.

Stomovlasis, D., & Tsaparlis, G. (2000). Non-linear analysis of the effect of working memory capacity on organic synthesis problem solving. *Chemistry Education: Research in Practice in Europe,* 1, 375-380.

Stowe, R., & Cooper, M. (2017). Practicing what we preach: assessing ‘‘critical thinking’’ in organic chemistry. *Journal of Chemical Education*, 94, 1852-1859

Sunyono, M., Yuanita, L., & Ibrahim, M. (2015). Mental models of students on stoichiometry concept in learning by method based on multiple representation. *The Online Journal of New Horizons in Education,* 5(2), 30-45.

Tsaparlis, G. (2005). Non algorithmic quantitative problem solving in university physical chemistry: A correlation study of the role of selective cognitive factors. *Research in Science and Technological Education*, 23, 125-145.

Underwood, S., Posey, L., Herrington, D., Carmel, J., & Cooper, M. (2018). Adapting assessment tasks to support three-dimensional learning. *Journal of Chemical Education*, 95, 207-217.

Zoller, U., & Tsaparlis, G. (1997). Higher and lower-order cognitive skills: The case of chemistry. *Research in Science Education*, 27, 117-130.