

PROBLEM SOLVING: HOW CAN WE HELP STUDENTS OVERCOME COGNITIVE DIFFICULTIES

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The traditional approach to teach problem solving usually consists in showing students the solutions of some example-problems and then in asking students to practice individually on solving a certain number of related problems. This approach does not ensure that students learn to solve problems and above all to think about the solution process in a consistent manner. Topics such as atoms, molecules, and the mole concept are fundamental in chemistry and instructors may think that, for our students, should be easy to learn these concepts and to use them in solving problems, but it is not always so. If teachers do not put emphasis on the logical process during solving problems, students are at risk to become more proficient at applying the formulas rather than to reason.

This disappointing result is clear from the outcomes of questionnaires meant to measure the ability to calculate the mass of a sample from the number of atoms and vice versa. A suggestion from the cognitive load theory has proved a useful way to improve students' skills for this type of problems: the use of worked out examples. The repetition after two weeks of the Friedel-Maloney test after the use of worked examples shows that students' skills significantly improve. Successful students in all questions jumped from 2 to 64%.

Keywords – Problem solving, worked examples, Psychological measurement, Problem representation, Cognitive architecture.

1 INTRODUCTION

An important and qualifying hallmark of teaching science is the ability to promote problem solving and critical thinking skills. It is critical that future citizens have skills in problem-solving to address the range of needs in their life and careers. Problem-solving is an important higher-order cognitive skill. "To solve a problem means to search for a way out of a particular difficulty; to find a way leading to the pre-set objective, which is not immediately attainable. Solving problems is a specific activity of mind, and mind is specific only for a human: thus, solving problems is fundamental human activity" (Polya, 1984, pp. 240). Some scholars connect problem-solving abilities with the definition of intelligence: "intelligence is by definition the ability to solve problems." (Nęcka & Orzechowski, 2005, pp. 127). According to John Anderson, "In understanding procedural knowledge we start with problem solving because it seems that all cognitive activities are fundamentally problem solving in nature." (Anderson, 1995, pp. 237). The Cambridge Handbook of Intelligence reported Wechsler's famous definition of intelligence: "the aggregate or global capacity of the individual to act purposefully, to think rationally and to deal effectively with his environment" (Willis, Dumont & Kaufman, 2011, pp. 50). According to Sternberg, (1988, pp. 72) intelligence "is the purposive adaptation to and selection and shaping of real-world environments relevant to one's life."

All these definitions highlight the connection between the idea of intelligence with the ability to solve problems and to engage in abstract thinking. Established the importance of problem solving, it is necessary to consider

what is the nature of a problem in cognitive science and the difference between a problem and an exercise. Problems come in many forms; a general definition of the term is bound to be abstract. A first and still valid definition comes from Karl Dunker: “A problem arise when a living creature has a goal but does not know how this goal is to be reached” (Dunker, 1945, pp. 1). According to John Hayes, “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 the gap, you have a problem” (Hayes, 1989, pp. XII).

From this definition, it follows that not all the 'problems' that are used in education are real problems: many are just exercises. Polya calls exercise a routine problem “which can be solved either by putting in special data in already previously solved general problem or so that a certain very shabby pattern is followed step by step, without any trace of originality.” (Polya, 1984, pp. 241) The “problem” notion is associated with cognitive difficulties and the application of knowledge and skills in logical reasoning in a different context. A helpful classification of problem types has been made by Johnstone (2001). He suggested that there are three variables associated with all problems: the data provided, the method to be used, and the goal to be reached. By looking at the two possibilities where each variable is either known or unknown, he came up with eight problem types. The type where each variable is known are not problems, but exercise. According to Jonassen, (2000, pp. 65) a problem is defined by two critical attributes: it “is an unknown entity in some situation (the difference between a goal state and a current state). Those situations vary from algorithmic math problems to vexing and complex social problems, such as violence in the schools. Second, finding or solving for the unknown must have some social, cultural, or intellectual value. That is, someone believes that it is worth finding the unknown.”

As teachers know from their teaching experience, it is not possible to distinguish between problems and exercises just by looking at the problem. The same task can be an exercise for a student and a difficult problem for another student. This is because “Status as a problem is a subtle interaction between the task and the individual struggling to find an appropriate answer or solution” (Bodner, 1987, pp. 513; Bodner & Herron, 2002, pp. 236).

However, the phrase ‘problem solving’ can be understood in many ways. Problem solving can be seen as the skills associated with solving numerical calculations, while others might think of practical skills in the laboratory. It is equally possible to see problems as the real-life problems faced, for example, by many people because of economic difficulties or problems associated with the depletion of the ozone layer or global warming. In this article we will restrict our analysis to the numerical calculations that a freshman meets in a chemistry college course.

The characteristic of the problems that are used in teaching is that they are well-structured and well-defined. Usually the real-world problems are not well structured. (Jonassen, 1997, pp. 68) In the literature there is a final distinction between problems: they can be well-defined and ill-defined problems. According to Kahney (1986, pp. 20), in a well-defined problem the solver is provided with several types of information:

- information about the initial state of the problem;
- information about the goal state;
- information about legal operators (operations that are legally allowed);
- information about operator restrictions which constrain their applications.

The well-known Tower of Hanoi problem can be an example of a well-defined problem. (Sapir, 2004, pp. 20) “Given are three pegs and a certain number n of disks of distinct sizes. Initially all disks are stacked on the first peg (the source) ordered by size, with the smallest at the top and the largest at the bottom. The goal is to transfer them to the third peg (the destination), while obeying the following rules:

- at each step only one disk can be moved;
- the moved disk must be a topmost one;
- at any moment, a disk cannot reside on a smaller one.”

We make explicit another restriction of the operator ‘move’ saying that the discs can only be moved in the 3 pegs. The next problem that the reader will encounter is another example of well-defined problem.

2 MEANINGFUL PROBLEM-SOLVING

Depending on whether a problem is well-structured or ill-structured, a different strategy is required to teach problem-solving skills in instructional settings. "Requiring learners to justify (argue for) their positions while solving problems (especially ill-structured problems) should be an essential part of problem-solving instruction." (Shin, Jonassen & McGee, 2003, pp. 28)

Solving a new problem requires the production of new knowledge; "new knowledge is produced through a series of cognitive activities acting on (external) information and prior knowledge." (Taconis, Ferguson-Hessler & Broekkam, 2001, pp. 444). The stoichiometric problems considered in a chemistry course can be described as closed and usually lead to a single 'right' answer. According to Frazer (1982, pp. 173), in closed problems there is 'a single unique solution', while 'most problems outside the classroom, do not have unique, unambiguously correct solutions – these can be called 'open problems'".

In what follows, well-defined and closed numerical problems will be considered: problems that require numerical calculations in the context of known theoretical domains for their solution.

Problem solving is a complex cognitive task in which critical thinking and metacognitive activity play an important role. According to Jonassen (1997, pp. 65-66), "Problem solving, as an activity, is more complex than the sum of its component parts. ... [it involves] domain knowledge, structural knowledge, ampliative skills, metacognitive skills, motivation/attitudinal components,..and certainly requires knowledge about self". It is necessary to teach the reasoning involved in the problem solutions in ways that are meaningful for students and make sense to them, because "research has made it clear that procedures must take on meaning and make sense or they are unlikely to be used in any situation that is at all different from the exact ones in which they are taught." (Resnick, 1983, pp. 478)

In teaching, it is also required to consider the limitations of human cognitive architecture without unnecessarily overloading the student's working memory. So, "when teaching new content and skills to novices, teachers are more effective when they provide explicit guidance accompanied by practice and feedback, not when they require students to discover many aspects of what they must learn." (Clark, Kirschner & Sweller, 2012, pp. 6) According to Shavelson (2010, pp. 11), "learning is about change in behaviour" and the purpose of instruction must be to increase the useful knowledge stored in the long term memory, because "If nothing has changed in long-term memory, nothing has been learned." (Sweller, Ayres & Kalyuga, 2011, pp. 24).

3 OBJECTIVES

The study on recurrent errors and difficulties encountered by students in solving chemical problems has been going on for many years. In this article the difficulties that students encounter in the calculations involving chemical formulas will be considered. In this study the information in terms of number of moles and molecules, and vice versa, will also be analyzed. According to the Johnstone's triangle (1991) this study will move in the side sub-microscopic – symbolic. For teachers who are experienced, the extensive use of symbols in chemical representations is a normal occurrence. Instead, the abstract nature of the chemical representations can mean to the student a significant increase of the mental load in the working memory. "The reader is invited to see chemistry students as similar to learners working in a second language, where they are expected to be both learning the language and using the language to understand substantive material simultaneously. This is considered more than a metaphor – and highlights the even greater challenge posed to those who are expected to learn this new language of chemistry as they learn the chemistry in the medium of a language that is already not their own." (Taber, 2009, pp. 78)

In 1996, students enrolled in a first year chemistry course in the faculty of Engineering of the Polytechnic University of the Marche were asked to solve this problem, bringing out all the steps: Consider the oxygen contained in 10.00 g of Fe_2O_3 . How many molecules of oxygen are equivalent to this quantity? (molar mass of Fe_2O_3 is 159.7 g):

- [A] 1.414×10^{22} ;
- [B] 2.262×10^{22} ;
- [C] 3.771×10^{22} ;
- [D] 5.656×10^{22} ;
- [E] NOTA. (NOTA means: none of the above).

The results were quite disappointing (responses' distribution are reported in Table 1): only 15 students out of 87 (17.2%) have given the correct answer ([D]). (Cardellini, 1996). The response distribution shows that students have great difficulty in reasoning:

N	[A]	[B]	[C]	[D]*	[E]
87	2.3%	3.4%	33.3%	17.2%	43.7%

Table 1. Responses' distribution to the problem: How many molecules of oxygen are equivalent to 10.00 g of Fe₂O₃?

The majority of students got the wrong solution because they used inconsistent relationships. For example, the typical wrong reasoning is 1 mol O₃ = 1 mol O₂. The use of this wrong relationship leads to the response [C] (one-third of the students have made this mistake). Instead, some of the responses [E] have used the procedure:

$$10.00 \text{ g Fe}_2\text{O}_3 = 6.262 \times 10^{-2} \text{ mol Fe}_2\text{O}_3$$

Because 1 mol Fe₂O₃ contains 3 mol O,

$$(6.262 \times 10^{-2} \text{ mol Fe}_2\text{O}_3) \times (3 \text{ mol O}/1 \text{ mol Fe}_2\text{O}_3) = 1.879 \times 10^{-1} \text{ mol O}$$

$$(1.879 \times 10^{-1} \text{ mol O}) \times (6.022 \times 10^{23} \text{ molecules O/mol O}) = 1.131 \times 10^{23} \text{ molecules O}$$

Given the confusion between atoms and molecules in the above solution (molecules O), at the time this Author suggested that some of the students do not know the difference between atom and molecule. This conclusion may seem excessive, but the word 'know' has different meanings in different contexts, at least from the operational point of view, when the concepts are inserted in stoichiometric calculations. Faced with the difficulties of the students, responsible teachers should ask themselves why students make mistakes and what we can do to help them to think properly. For teachers, as experts, it is difficult to understand the difficulties of students, also because teachers have forgotten the difficulties, when for the first time they solved the same problems. It is worth reflecting on the observation of Keith Taber, (2009, pp. 81) "Where the expert has developed interpretive frameworks that can 'see through' the symbols, the novice may focus on incidental aspects of the formalism used."

The objective of this study is to find strategies, instructions, or tips for students to improve their skills in the solution of these problems. According to Merrill (2002, pp. 47) "Learning is promoted when learners are provided appropriate learner guidance" Students experiencing difficulties in relationships among the atomic mass, the molar mass, the mass of the substance, the meaning of the subscript, and the difference between atoms and molecules. This aspect has been highlighted many years ago in the literature: "Historically, teachers of beginning chemistry have named the mole concept as the most difficult part of the beginning course. What teachers have in mind is not the concept alone, however: instead they include many relationships and calculations that involve the mole." (Dierks, Weninger & Herron, 1985, pp. 839)

Because the representation of the problem is an important step in solving the problem, and the use of a correct representation is indispensable to avoid errors, it was suggested the use of representation, associate with the use of proper stoichiometric ratio. In general, "A problem representation is a cognitive structure corresponding to a problem, constructed by a solver on the basis of his domain-related knowledge and its organization" (Chi, Feltovich & Glaser, 1981, pp. 121-122). The use of this procedure helped students and 94.4% of them have successfully solved a similar problem (Cardellini, 1996). Visualizing the formulas helps students determine the correct stoichiometric relationship between the number of atoms and so decreases working memory load.

However, because schools and students have changed through years, it may be interesting to ask whether this strategy is still valid and sufficient to improve the skills of the majority of the students. To address this question, a study was designed which engaged students enrolled in the first year of a chemistry course in a faculty of

Engineering. In this study, some cognitive styles and the students' perceptions about the course were explored to see if there was any relationship between these results and students' abilities in problem solving and the quality of the creative work resulting from this approach.

4 METHODOLOGY

In chemistry, as in other situations, acquiring the knowledge of relevant rules is not sufficient. "We can learn the rules of chess in about 30 min and using those rules, we can theoretically generate every game that has ever been played and that ever will be played. Learning those rules is essential to chess skill but in another sense, it is trivial. Real chess skill comes from acquiring automated schemas." (Sweller et al., 2011, pp. 24) The same thing can be said in stoichiometric calculations. To know about atoms, molecules, the Avogadro number, molar mass and moles is not sufficient to manage the cognitive skills necessary to master the reasoning that the correct concatenation of the steps require. It is also necessary to know the theory and do a lot of exercises to become proficient problem solvers. Students enrolled in courses where I teach are requested to solve many problems, to draw concept maps and résumés (write short summaries) using the concepts of the lectures. They are asked also to explain and justify the various steps of the solution of a problem and to develop a way for verifying the result. After each lesson, students receive e-mails with suggestions about exercises to be solved, the list of concepts presented in class and a copy of the slides for the next lesson.

The study was designed by measuring the students' ability in the calculation with a test on the first day of the course and the repetition of the same test after the intervention. The instrument used was the Friedel-Maloney test, with the addition as the first question of the above problem unidentified. This is also because the results of the four different questions in the test are always different from each other. Also, the solution of the calculation of molecules of oxygen in 10.00 g of Fe_2O_3 requires conceptual passages similar to the problems that students must solve in written examinations.

The Friedel-Maloney test "determine(s) what our students are able to do with the information presented in class about moles, molecules, atoms, gram atomic weight, Avogadro's number, and molar mass." (Friedel & Maloney, 1995, pp. 900). The Friedel-Maloney is a paper and pencil test using a four multiple-choice options task and some results in the past have been reported elsewhere (Angawi & Cardellini, 2011). Over the years, the test was repeated, as were the more or less disappointing results. The Friedel-Maloney test measure the ability to use the relationship among the atomic mass, the molar mass, the mass of the substance, and Avogadro's number, and calculations involving atoms and molecules, by means of four problems:

- How many oxygen atoms are present in a container with 288 g of O_3 ?
- There are 1.8×10^5 atoms in a sample of P_4 . What is the mass of this sample?
- How many atoms of sulfur are in a sample of 963 g of S_6 ?
- There are 2.41×10^{24} atoms in a sample of S_8 . What is the mass of this sample?

This study reports the data obtained in three different courses, in different academic years. All relate to students enrolled in the first year of chemistry at the Faculty of Engineering of the Polytechnic University of the Marche. The first course in this study had 88 freshmen students enrolled in the first year of a chemistry course which took place in the second semester of the academic year 2012-13. Of these, 51 were male (58%) and 37 female (42%). The age of students was 19 - 21, with 2 students aged 22. The course was held in the second semester of the academic year 2012-2013, for a workload of 6 ECTS credits. In the 48 hours of the course, more than 4,500 solutions of stoichiometric problems were collected ($N = 32$ Ss; with a mean of 143.1 and standard deviation of 45.4). From the 32 students that passed the exam, 210 concept maps and 1,235 résumés were collected.

Three psychological measurements were applied to the group to see if there was any relationship between these results and the quality of the creative problem solving resulting from this approach. These were

- Formal Operational Reasoning,
- Disembedding Ability, and
- Convergent/divergent cognitive style.

The Formal Operational Reasoning was measured using the Group Assessment of Logical Thinking (GALT) test (Roadrangka, Yeany & Padilla, 1983). The scores ranged from 8 to 22 (out of 24) with a mean of 16.6 and standard deviation of 3.6. The disembedding ability was measured by the Field Dependence/Field

Independence test devised and calibrated by El-Banna (1987) based upon the original work of Witkin (Witkin, 1974; Witkin & Goodenough, 1981). Out of a possible score of 20, the range achieved was 5-19, with a mean value of 13.7 and a standard deviation of 3.9. According to Danili and Reid (2004) the extent of field dependency influences all academic performance.

The Convergent/Divergent test consisted of 6 mini tests, developed and calibrated at the Centre for Science Education in the University of Glasgow, UK, and described elsewhere (Danili & Reid, 2006). In the Italian translation, the only difference was on test 5: it was adapted to the Italian language and students were asked about the words, which begin with the letter G, and end with the letter A.

The usual modest results were repeated, but the disappointment was even greater considering the results of the second round of the Friedel-Maloney test. The distribution of students' responses are reported in Table 2. The first question: Consider the oxygen contained in 10.00 g of Fe_2O_3 . How many molecules of oxygen are equivalent to this quantity? (molar mass of Fe_2O_3 is 159.7 g):

<i>N</i>	<i>a</i>	<i>b</i>	<i>c</i>	<i>d*</i>	<i>e</i>
55	0	2	41	3 (5.45)	9
47	0	0	8	33 (70.2)	6

Table 2. The distribution of students' responses to the first and second rounds respectively, of the problem: How many molecules of oxygen are equivalent to 10.00 g of Fe_2O_3 ?

The second question (Results are reported in Table 3): How many oxygen atoms are present in a container with 288 g of O_3 ? (molar mass of O_3 is 48.0 g):

- (a) 3.61×10^{24} ;
- (b) 18.0;
- (c) 1.08×10^{25} ;
- (d) 1.20×10^{24}

<i>N</i>	<i>a</i>	<i>b</i>	<i>c*</i>	<i>d</i>
55	46	1	8 (14.5)	0
47	11	0	36 (76.6)	0

Table 3. The distribution of students' responses to the first and second rounds respectively, of the problem: How many oxygen atoms are present in a container with 288 g of O_3 ?

The third question (the distribution of students' responses are reported in Table 4): There are 1.8×10^5 atoms in a sample of P_4 . What is the mass of this sample? (Molar mass of P_4 is 124 g.):

- (a) 9.3×10^{-18} ;
- (b) 3.7×10^{-17} ;
- (c) 5.6×10^6 ;
- (d) 1.5×10^{-16}

<i>N</i>	<i>a*</i>	<i>b</i>	<i>c</i>	<i>d</i>
55	3 (5.45)	50	2	0
47	9 (19.1)	37	1	0

Table 4. The distribution of students' responses to the first and second rounds respectively, of the problem: There are 1.8×10^5 atoms in a sample of P_4 . What is the mass of this sample?

The fourth question (the distribution of students' responses are reported in Table 5): How many atoms of sulfur are in a sample of 963 g of S_6 ? (gram atomic weight of S is 32.1 g):

- (a) 3.01×10^{24} ;
- (b) 30.0;
- (c) 5.02×10^{23} ;
- (d) 1.81×10^{25}

<i>N</i>	<i>a</i>	<i>b</i>	<i>c</i>	<i>d*</i>
55	16	1	0	38 (69.1)
47	11	0	0	36 (76.6)

Table 5. The distribution of students' responses to the first and second rounds respectively, of the problem: How many atoms of sulfur are in a sample of 963 g of S_6 ?

The last question (the distribution of students' responses are reported in Table 6): There are 2.41×10^{24} atoms in a sample of S_8 . What is the mass of this sample? (gram atomic weight of S is 32.1 g):

- (a) 16.1 g;
- (b) 7.74×10^{25} g;
- (c) 128.4 g;
- (d) 9.68×10^{24} g;
- (e) 1.03×10^3 g

<i>N</i>	<i>a</i>	<i>b</i>	<i>c*</i>	<i>d</i>	<i>e</i>
55	0	2	33 (60)	2	18
47	0	0	25 (53.2)	0	22

Table 6. The distribution of students' responses to the first and second rounds respectively, of the problem: There are 2.41×10^{24} atoms in a sample of S_8 . What is the mass of this sample?

I asked for advice Prof. John Sweller of the University of New South Wales in Sydney, Australia, who originated cognitive load theory. The suggestion was to train students with the use of the worked example method. (Sweller & Cooper, 1985) A worked example provides learners with information concerning a problem solution. A worked example not only shows the sequence of steps, but also comments on them with explanations and their motivation. Five problems, three suggested problems to be solved, and two worked problems, solved with the intention to "direct attention appropriately and reduce cognitive load" (Ward & Sweller, 1990, pp. 1), were used in this experiment in two different courses.

The second course in this study had 77 freshmen students enrolled in the first year of a chemistry course which took place in the first semester of the academic year 2013-14. Of these, 55 were male (71%) and 22 female (29%). The age of students was 19-21, with 2 students aged 23 and 25 years old. The course was held in the first semester of the academic year 2013-2014, for a workload of 9 ECTS credits. In the 72 hours of the course more than 7,000 solutions of stoichiometric problems were collected ($N = 49$ Ss; with a mean of 145.3 and standard deviation of 87.8, from 22 to 373 solutions). In Figure 1 the collected solutions to this and other courses are shown.



Figure 1. Despite the workload required in the course, many students were quite happy to work in this way. In a questionnaire completed by students after passing the exam, the question: There was too many problems to be solved scored 3.03, while the question: I like to solve stoichiometric problems scored 5.50 out of 6 (N = 30 students)

Psychological measurements: The scores of the GALT test (N = 61) ranged from 10 to 24 with a mean of 19.5 and standard deviation of 3.1. It seems that having a high GALT score helps: all but 3 students who solved correctly the five problems achieved a score greater than 19. The results of the disembedding ability test (N = 48) ranged from 3 to 17 with a mean of 10.4 and standard deviation of 3.1, while the results of the Convergent/Divergent test (N = 40) ranged from 25 to 68 with a mean of 50.0 and standard deviation of 10.0. In advancing the course, the number of students decreased because many students dropped out of school. 16 students who solved correctly the five problems achieved a score greater than the mean value in the test of disembedding abilities, while 10 students achieved a score greater than the mean value in the Convergent/Divergent test.

The results of pre-post intervention study indicate a significant improvement in the ability to solve these types of problems. In the first test proposed in the first day of the course, 13 students had all the answers wrong while only one solved correctly all 5 questions. In the second test proposed after two weeks, 27 solved all 5 questions correctly. As in the previous course, between the two tests, in addition to worked examples students have solved a number of problems found in the text of stoichiometry Figure 2 reports the results of the solutions to the question: Consider the oxygen contained in 10.00 g of Fe_2O_3 . How many molecules of oxygen are equivalent to this quantity? (molar mass of Fe_2O_3 is 159.7 g).

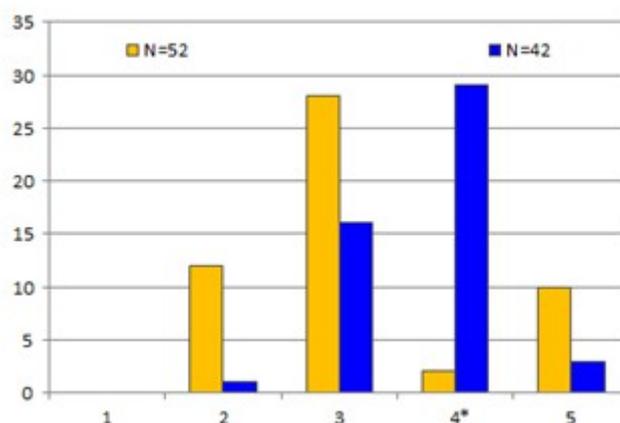


Figure 2. The correct answer (4) increased from 4% to 69% after the study and working on the worked example experiment

In Figures 3 and 4 are reported the results of the solutions of the second and third questions, respectively.

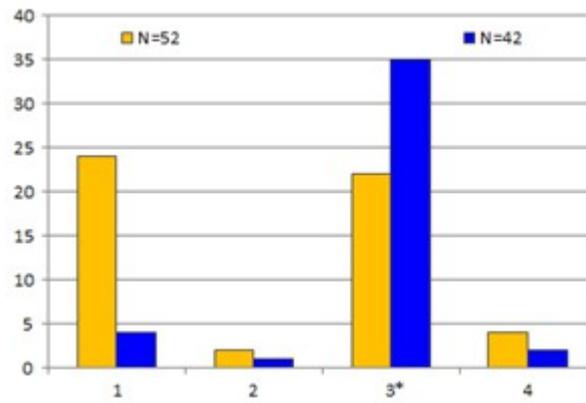


Figure 3. The correct answer (3) increased from 42% to 83%

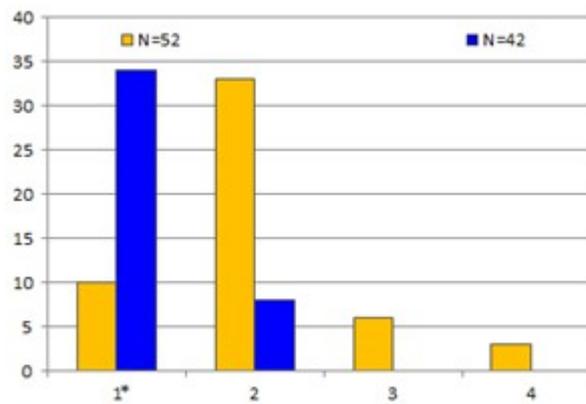


Figure 4. The correct answer (1) increased from 19% to 81%

In Figures 5 and 6 are reported the results of the solutions of the fourth and fifth questions, respectively.

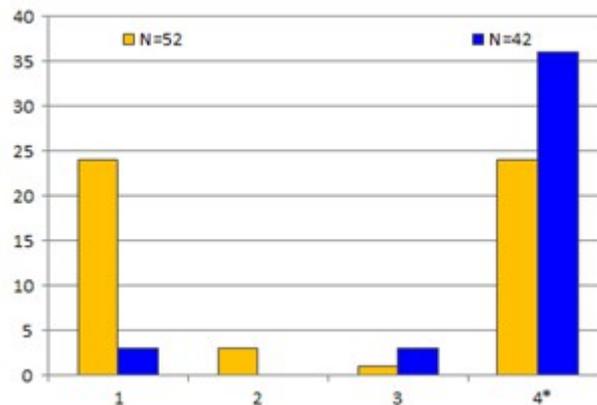


Figure 5. The correct answer (4) increased from 46% to 86%

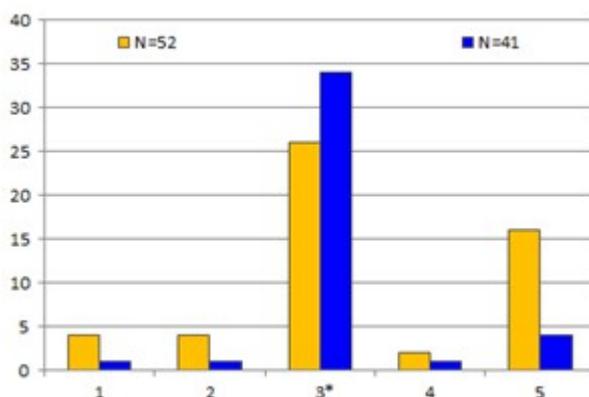


Figure 6. The correct answer (3) increased from 50% to 83%

As additional proof I report other results from students enrolled in a course that was held in the first semester of the academic year 2013-2014, for a workload of 6 ECTS credits. Even if the three courses here described in part differ in content, up to the part of stoichiometric calculations reported in these studies, the three courses have proceeded in exactly the same way. In the first test (N = 48), 18 students had wrong answers on all questions, in the second test (N = 39), 22 students solved correctly all 5 questions. The correct answers increased from 8% to 74% in the first question, from 13% to 85% in the second, from 11 to 64% in the third question, from 59% to 82% in the fourth, and from 51% to 77% in the last.

5 CONCLUSIONS

Knowledge of the difference between atoms and molecules and the stoichiometric relationships between atoms in chemical formulas are taken for granted. In the university teaching of stoichiometric calculations, this part of chemistry has very little time devoted to it. This is a shame because as these studies demonstrate, there are many conceptual difficulties students encounter in solving problems requiring stoichiometric calculations.

The results obtained with the use of worked examples are very encouraging. The representation of the problem is certainly an important aspect in problem solving, but even more important are the logical processes that help solve the problems correctly. The adoption of worked examples really helped the students to improve their skills in this part of stoichiometric calculations.

It must be remembered that we can't teach people to solve all novel problems better. What we can do, is turn novel problems into exercises. Worked examples can help in that aim. "The purpose of worked examples is precisely to turn problems into exercises. Once sufficient knowledge concerning the problems of an area has been stored in long-term memory, all problems become exercises and high levels of expertise have been attained." (Sweller, 2014)

Another educational aspect deserves to be considered. During the course my students usually work in cooperative groups, according to some role, exercising and practicing solving numerous problems. In this way they also become skilled at solving more complex problems. This is an important aspect of meaningful learning because "explaining another person's reasoning, especially a more correct one, raises additional opportunities for comparing and contrasting the other person's reasoning with one's own. Any conflicts observed will naturally elicit more repairs of one's representation. ... exposing a learner to multiple perspectives on a problem (or perhaps even multiple representation of a problem solution), either from a text or from another peer's reasoning, seems to support effective explaining and thereby learning. (Roy & Chi, 2005, pp. 276-277)

In this experiment, the students have solved problems involving atoms, molecules, and formulas individually. We do not know what happens in more complex problems. Because skill is very domain-specific, probably we will need the use of a greater number of worked examples to prepare students. This study highlights that many students (about 35% of them) continue to have difficulty with this kind of problem. In addition to working in cooperative groups, less skilled students need more guided instruction. "It appears that guided instruction helps less skilled learners by providing task-specific learning strategies." (Clark et al., 2012, pp. 8).

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