Fostering creative problem solving in chemistry through group work

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Abstract: Although problem solving is a very important higher-order cognitive skill, our students seem to believe that this activity does not deserve too much effort and they develop the attitude that arriving at the answer is more important than understanding the process of solution. This is due in part to the way we teach problem solving. Usually, when teaching, we show them only some stages of the process, neglecting the analysis stage, because as experts we are now no longer able to recall the effort we had to expend the first time we tried to solve a problem, since it is now familiar to us. From our presentation, students see a clean, even elegant solution, having little in common with the uncertainty and the fuzzy thinking that they experience when they try to solve a problem by themselves. From research we know that it is quite difficult for students to develop creative solutions to problems. The results reported here are promising in making students active developers of original solutions. These results are tentatively attributed to the use of an active method of learning and to the students' motivation. [*Chem. Educ. Res. Pract.,* 2006, **7** (2), 131-140]

Keywords: problem solving; problem representation; creativity; cooperative learning; analysis skills; learning styles.

Introduction

Problem solving is very important for many subjects. Chemistry is no exception, combining in its problems characteristics of mathematics and physics problems, and adding its distinct chemical features (stoichiometry, chemical synthesis, chemical analysis, etc.). In stoichiometry, important quantitative relations constitute conceptual building blocks. But problem solving is a higher-order cognitive skill (Zoller, 1993) which demands many abilities, sometimes requiring much effort from the solver. Problem solving is a process in which various reasoning patterns are combined, refined, extended, and invented. It is much more than substituting numbers in well-known and practised formulas; it deals with creativity, lateral thinking and formal knowledge. Research has tried to correlate some cognitive variables, such as formal operational reasoning, working memory capacity, disembedding ability, specific knowledge, concept relatedness and idea association, to science achievement and problem solving ability (Mayer, 1975; Johnstone and El-Banna, 1986; Niaz, 1987; Camacho and Good, 1989; Niaz and Logie, 1993; Tsaparlis et al., 1998; Stamovlasis and Tsaparlis, 2000; Lee et al., 2001).

Suggestions from research are, that instructional methods should take into account the general strategies and methods of problem solving, thus providing a tool to increase reasoning skills in the problem solver. Life is, in essence, a continuous process of problem solving and selection from available and/or created options, and it is sobering to note that sometimes people who have received formal training in problem solving are not necessarily the best problem solvers. Nevertheless, problem solving abilities/decision making capacities are valuable and precious skills not only in academia, but also in the world of business and industry and in daily living. Furthermore, in science these skills play an important role in the acquisition and organisation of knowledge in a meaningful way. The way knowledge (both 'know-how' and 'know-what') is organized in memory is generally recognized to be critically related to the degree of success in problem solving (De Jong and Ferguson-Hessler, 1986). To help students organize and structure their knowledge, they are asked to draw concept maps (Novak and Gowin, 1984; Novak, 1998) for every topic presented in the course syllabus.

Access to knowledge

If an important prerequisite for being a successful problem solver is that knowledge must be activated in the Long Term Memory (LTM) when needed, this must have implications for the way we teach and the way in which students are encouraged to lay down knowledge in LTM. If the research on learning styles (Entwistle, 1988; Lawrence, 2000) is to be taken seriously, we have to admit that a lecture may not be the best way to facilitate the orderly linkage of knowledge in LTM. Not surprisingly, research shows that note-taking is affected by a person's information processing ability and by individual psychological factors such as field dependence/independence (Johnstone and Su, 1994). Moreover, students taught almost entirely in a way that clashes with their learning styles, do not learn as much as students taught in their preferred styles, and they retain less of what they learn (Felder, 1996a).

Many years ago, Whitehead warned about the danger of knowledge that is accessed only in a restricted set of contexts even though it is applicable to a wide variety of contexts, and he called it inert knowledge (Whitehead, 1953). Knowledge stored in sealed boxes without meaningful connections with other concepts is inert knowledge. This point is illustrated by Johnstone in another paper in this issue of CERP, where he reports on the problem of teaching senior undergraduates in bioinorganic chemistry. Students complain that in the same lecture they are meeting concepts of thermodynamics, complex formation and stability and organic ligands. It is clearly very uncomfortable for them to "*open several boxes at once*". (Johnstone and Otis, 2006).

Several factors influence the abilities in solving problems, from the nature of the problem, to the learners' developmental level and their knowledge base, to motivation and problem solving skills, to many individual and psychological factors. A deep and comprehensive analysis of those factors can be found in the literature (Reid and Yang, 2002).

This study looked at a group of engineering students (21 girls and 24 boys, aged 19-22) in the first term of their first year at university. Two 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 (a) Formal Operational Reasoning and (b) Disembedding Ability.

The former was measured using the Group Assessment of Logical Thinking (GALT) test (Roadrangk et al., 1983). The scores ranged from 11 to 24 (out of 24) with a mean of 19.5 and standard deviation of 3.2.

The latter 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 and Goodenough, 1981). Out of a possible score of 20, the range achieved was 4-19, with a mean value of 14.0 and a standard deviation of 3.4.

As we see in the literature, the development and improvement of education requires the fostering of creativity and critical thinking (CT) skills: "*Critical thinking is reasonable reflective thinking that is focused on deciding what to believe or do.*" (Ennis, 1987) There is no question that many teachers would like to improve the CT abilities of their students. How can this be done? Or, in the Schoenfeld words: "*The critical question is: can we train novices to solve problems as experts do?*" (Schoenfeld, 1980).

To become an expert in any domain, a lot of work is needed. It is estimated to take about 10,000 hours; a much longer time than any undergraduate course (Hayes, 1988). However, the experience described in this paper suggests that something valuable can be achieved in a short time. In their seminal work, Larkin et al. (1980) found four differences between experts and novices. Glaser and Chi (1988) enumerate seven characteristics of experts, but the difference, which is of major importantance for the novice, is that the expert spends a great deal of time analysing a problem qualitatively. In light of this thought, it was our hypothesis that students can be more successful in problem solving if they get accustomed to spending more time in analysing problems. The experience described in this paper is an attempt to encourage students to analyse problems and to apply novel methods to their solution.

Attempting to improve analysis skills

As teachers we believe that working on problems is an effective way to learn. Unfortunately, our students usually develop the attitude that arriving at the answer is more important than understanding the solving process. Many students start to calculate something from the text of the problem, without ever asking themselves whether this calculation will get them closer to the correct solution. Why might this be so? "*Textbook solutions to problems and solutions presented by instructors on the blackboard are always efficient, well-organized paths to correct answers*." (Herron, 1986) They apply algorithms developed by experts after repeated solutions of similar problems. "*They provide no indication of the false starts, dead ends, illogical attempts, and wrong solutions that characterize the efforts of students when they work in problem solving.*" (Herron, 1990; Bodner, 2003)

If we want to help our students, we have to find a different way to teach problem solving, a way that obliges students to spend more time analysing the problem. It was decided to try a fresh approach to teaching problem solving based upon the Analysis, Synthesis and Verification (ASV) method developed by the author (Cardellini, 1984) and incorporating the use of a cooperative approach involving small group working.

The initial problems tackled were non-chemical and non-algorithmic to emphasise the analysis and synthesis operations without the interference of chemical concepts which students may not have mastered as yet. Examples of the kind of problems are shown below.

Problem 1. Consider two containers, A and T. Container A has 10 mL of water in it from the Adriatic Sea; T contains 9 mL of water from the Tyrrhenean. Suppose that 1 mL of Adriatic water are removed from container A and put into T. After the liquid in T is mixed thoroughly, 1 mL of the mixture is removed and added to the contents of container A. Which container now has the greater amount of foreign water, the Adriatic water being foreign to T, or the Tyrrhenean to A? (Adapted from Case, 1975)

Problem 2. Two friends meet after a long time. While catching up on each other's news, one discovers that the first has married and has three sons. Then the second asks their age and the first one answers – "*the product of their ages is 36, and their sum is equal to that house number there*" – pointing to the number under the porch of the house. But the second replies – "*it is not sufficient.*" And the first one – "*OK. Then I will also add that the youngest has blue eyes.*"

Without any familiar algorithms to depend upon, students had to reason their way into the problems, draw diagrams (if necessary) to represent the problems and then, having analysed them, to plan a method for their solution. At the end came the verification of the results to be assured of their reasonableness. The ASV approach was aided by a number of questions which helped the students to subdivide the problems to reduce the load on Working Memory.

A key feature of the approach was small group working. (See Wood's paper in this issue; Wood, 2006). The class was organised into groups of three, giving seven groups of girls and eight of boys. Before starting on the problems, they were briefed in the use of concept maps (to aid the problem analysis) and in the techniques of group work. Effort has to be made to try to change the students' attitude toward problem solving: to shift the focus from looking at the product (the solution) to the importance of viewing problem solving as a conscious reasoning process.

Solving these problems requires time and it is not possible to apply a formula to them, so students have to use their reasoning. Maybe for the first time, students have to use some heuristic strategies such as decreasing the complexity of the problem, breaking down the task into subproblems, making the problem visible by translating it into pictures, diagrams or graphs, solving an analogous problem, or even working backwards, if this can help.

The first stage in problem solving is probably where the solver works hardest trying to understand the problem, extracting relevant information and translating it, or part of it, into a familiar form. "*This is a holistic or gestalt stage where relevant information is 'disembedded' from the problem, and the elements of the problem are juggled more or less simultaneously until the problem is 'restructured' or transformed into a problem that the student understands*" (Bodner and McMillen, 1986).

In this method of teaching problem solving, there is a special way of dealing with the students' errors. When the students have solved the problem in groups, one of them presents the solution on the blackboad, which is then discussed with the class. The same is done with the wrong solutions. At the end of every lesson, some problems are suggested as homework. Before starting each lecture, comments are made on the problems collected and corrected the day before, and the new problems are collected for correction.

The cooperative learning approach in detail

Cooperative learning is a method of active learning where students are involved in some activity beyond listening to the teacher. In the past students have been expected to learn how to solve problems by looking at the way teachers solve the problem at the blackboard. Instead, in this approach the students are actively involved in the learning process. Students tackle problems in groups, according to certain roles (Problem solver, Sceptic, Checker/Recorder) and follow a structured procedure under conditions that meet the five criteria of cooperative learning set out below (Johnson, Johnson and Smith, 1991; Felder, 1996b).

1. *Positive interdependence.* Team members must rely on one another to accomplish goals.
2. *Individual accountability.* Members are held accountable for (a) doing their share of the work and (b) mastering all material.
3. *Face-to-face interaction.* Some or all of the work is to be done by members working together.
4. *Appropriate use of interpersonal skills.* Team members practise and receive instruction in leadership, decision-making, communication and conflict management.

5. *Self-assessment of group functioning.* Teams periodically reflect on what they are doing well as a team, what they could improve, and what they will do differently in the future.

According to this method, the Problem solver has to think aloud, and the Sceptic has to understand the solution, asking for explanations when necessary. By working in groups, students are more likely to activate some critical thinking process. So the role of the Sceptic is very important, especially if he helps the Problem solver to move away from assumptions which might lead to a dead end. Because, for every new problem, the roles rotate, every student has the opportunity to improve her/his capacity in the analysis, synthesis and verification processes. Thinking aloud has the additional benefit of reducing the speed of the thinking process, discouraging jumping to conclusions and improving the chances of arriving at a more accurate conclusion. Constructing the solution in the group, negotiating the meaning, explaining inferences, teaching one another, making sense of the relationships facilitates the deep understanding of the solution. Making the groups work fruitfully, requires competence in applying the cooperative learning method, and effort from the teacher.

The students were told that there would be less class time spent on lectures and about half the time or more on problem solving. Since problem solving is so important, they were promised that I would correct *every* single problem they solved and give each of them my opinion and suggestions on their solution. I explained why this was being done, assuring the students that it was not an expedient to make my life easier – quite the contrary, but in this way they would learn more and they would become more confident in their abilities. Experience shows that students learn in a more meaningful way if they teach one another some of the time rather than just listen to lectures (Cardellini, 2000a).

They were reminded that this method of problem solving also would prepare them for their professional careers where they would certainly have to work in teams. Before each new lesson (three lessons amount to seven hours every week), students were asked to sit according to their groups, and the maps they had constructed and the problems they had solved as homework were collected. Then the maps collected and corrected the day before were given back, with advice on how to improve them, and from time to time, someone was asked to come to the blackboard to answer questions about the material reported on the map. This was done to be sure that they had studied the theory behind the problems, and to make sure that I had explained it properly. They had my cell-phone number and my e-mail address. They knew they could ask me about anything that was not clear, but they also knew they needed to be prepared when they came to the class.

Students were quite happy to work in this way and play according to the rules. In the 50 hours of the course more than 1900 solutions of problems were collected and corrected. The best 10% of the students (final mark in chemistry $\geq 27/30$) solved, on average, 62 individual problems (ranging from 37 to 83). Almost all of them tried to solve problems in a creative way. The majority of the remaining students successfully solved at least one problem in a creative way. Several students verified their results according to the ASV method, but few solved all the problems using (the three formal steps of the method) ASV entirely. The time spent in verifying the result was quite valuable, and from the solutions in my collection there is proof that many students understood why and where they made errors and were able to correct themselves. None of the weak students verified the result of their solutions.

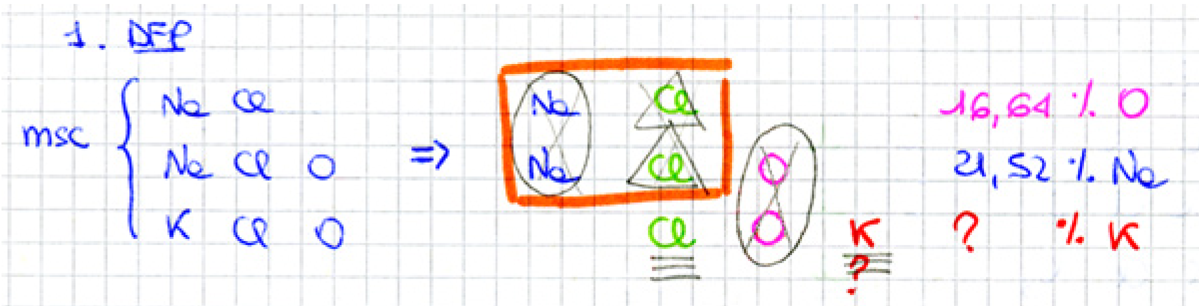
Some examples of creative solutions devised by students

Student 1

A mixture formed by NaCl, NaClO and KClO contains 16.64% of oxygen and 21.52% of Na. Calculate the percentage of K in the mixture (mxt).

1. Formal definition of the problem

She represented the problem by looking at the chemical formulas in this way:



From the total mass, subtracting the oxygen and the sodium, the mass of Cl and K will be obtained. In NaCl and NaClO, Na and Cl are in the same ratio: subtracting Na from (total) Cl, Cl in KClO is obtained because it is in stoichiometric relation with K. She considered 100.0 g of mixture (mxt).

2. Selection of appropriate information

Atomic masses: 16.00 g O/1 mol O; 22.99 g Na/1 mol Na; 35.45 g Cl/1 mol Cl; 39.10 g K/1 mol K.

100.0 g mxt – (21.52 g Na + 16.64 g O) = 61.84 g K + g Cl.

21.52 g Na ≡ 9.361 x 10^{-1} mol Na ≡ mol Cl in NaCl and NaClO.

3. Combine the various information

g Cl (in NaCl) + g Cl (in NaClO) = (9.361 x 10^{-1} mol Cl) x (35.45 g Cl/mol Cl) = 33.18 g Cl

(g K + g Cl) in KClO = 61.84 (g K + g Cl) – 33.18 g Cl = 28.66 g

74.55 g KCl : 39.10 g K = 28.66 g : x g K

x = 15.03 g K

Verification

74.55 g KCl : 90.55 g KClO = 28.66 g KCl : x g KClO

x = 34.86 g KClO

34.86 g KClO – 28.66 g KCl = 6.202 g O (in KClO)

16.64 g O – 6.202 g O = 10.44 g O (in NaClO)

16.00 g O : 22.99 g Na = 10.44 g O : y g Na

y = 15.00 g Na ≡ 48.57 g NaClO

21.52 g Na – 15.00 g Na = 6.52 g Na (in NaCl) ≡ 16.57 g NaCl

16.57 g NaCl + 48.57 g NaClO + 34.86 g KClO = 100.0 g mxt

Student 2

Here is another ingeneous solution (Cardellini and Felder, 2004):

22.99 g Na : 21.55 g Na = 35.45 g Cl : x g Cl; x = 33.18 g Cl (in NaCl and NaClO)

100.0 g mxt – 21.52 g Na – 33.23 g Cl – 16.64 g O = 28.66% KCl

74.55 g KCl : 28.66 g KCl = 39.10 g K : y g K; y = 15.03% K

Student 3

Another student developed this interesting and very sophisticated solution. This is a strategy that Marvin Levine (1994) called "*Look at the extremes*".

If the % of NaClO = 0, then 21.52 g Na are all from NaCl and 16.64 g O are from KClO. How many grams of NaCl there are in the mixture?

58.44 g NaCl : 22.99 g Na = x g NaCl : 21.52 g Na; x = 54.70 g NaCl

100.0 g mxt – 54.70 g NaCl = 45.30 g KClO

How many grams of oxygen there are in this mixture?

90.55 g KClO : 16.00 g O = 45.30 g KClO : y g O; y = 8.004 g O (the minimum content of O in the mixture).

If NaCl = 0, then 21.52 g Na are all from NaClO. How many grams of NaClO there are in the mixture?

74.44 g NaClO : 22.99 g Na = z g NaClO : 21.52 g Na; z = 69.68 g NaClO

100.0 g mxt – 69.68 g NaClO = 30.38 g KClO

How many grams of oxygen there are in this mixture?

[(69.68 g NaClO/74.44 g NaClO) + (30.38 g KClO/90.55 g KClO)] x (16,00 g O) = 20.34 g O (the maximum content of O in the mixture).

KClO can vary from 45.30 g to 30.38 g, and this make the variation of oxigen in the mixture from 8.004 g to 20.34 g.

Variation of KClO: 45.30 g – 30.38 g = 14.94 g

Variation of O: 20.34 g – 8.004 g = 12.34 g

(12.34 g O) x (1 g KClO)/(14.94 g KClO) = 8.260 x 10^{-1} g O

16.64 g O – 8.004 g = 8.636 g O

8.636 g O/8.260 x 10^{-1} g O = 10.46 (variation of KClO)

45.30 g KClO – 10.46 g KClO = 34.84 g KClO in the mixture

(34.84 g KClO)/(90.55 g KClO/mol KClO) = 3.848 x 10^{-1} mol KClO

(3.848 x 10^{-1} mol KClO) x (1 mol K/1 mol KClO) = 3.848 x 10^{-1} mol K

(3.848 x 10^{-1} mol K) x (39.10 g K/mol K) = 15.04 g K

The set of problems used in this study can be found in the appendix.

Another original solution for a similar problem, developed by two students who worked cooperatively, has already been reported (Cardellini, 2000b).

Discussion

Students are not obliged to solve the difficult problems that are presented during the course, but know that they can get a bonus if they are able to solve the problem in a way that are judged appropriate, original or new. Almost a third of students solved the problems by their reasoning to find a creative solution. This is an important result, since examples of creative problem solving are reported to be very rare (Treffinger and Ripple, 1971; Mayer, 1992). For the creative students, their GALT scores were equal to or greater than 18. Their disembedding scores were equal to or greater than 15. The creative problem solvers were clearly in the upper part of the distribution of formal reasoning skills and were also able to disembed relevent information from its surroundings in a problem. The majority of these creative students turned out to be very successful in the overall chemistry assessment as well as in their other subjects. Cognitive skills seem to have a role in successful problem solving, but personal motivations may be equally decisive (Hofstein and Kempa, 1985).

Conclusion

The approach to this problem solving experience is based on a constructivist view of learning which was summarized in a single statement by Bodner, "*Knowledge is constructed in the mind of the learner*." (Bodner, 1986) Students are actively engaged in finding the correct solution to the problem proposed and in making sense of the solution. They know that, at the end of the task, one of them will be called to the blackboard to explain the procedures used during that group's solution to the whole class and that a discussion will take place. The role of the teacher is mainly as a coach, a stimulus for reaching new goals. Students are asked to work in what is called the Zone of Potential Development (Brown and French, 1979). By working in a group they solve problems that they would be unlikely to solve alone. The method offers the students an environment in which they can learn and be motivated to learn as much as they can. This can be seen as an example of the experience enjoyed by the student who said, "*They didn't teach me anything, but I learned a lot.*" (Moore, 1996).

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Appendix

The following problems are ordered from the easiest to the most difficult. Many students solved problem no.1; few solved problem 4 and almost no one tried problem 5.

Relative atomic mass: H=1.008; C=12.01; O=16.00; Na=22.99; S=32.07; Cl=35.45; K=39.10; Mn=54.94.

1. A mixture formed by NaCl, $NaClO_3$ and $KClO_3$ contains 33.40% of oxygen and 16.00% of Na. Calculate the percentage of K in the mixture (Cardellini, 1999; p. 68).

2. A mixture of NaCl, $NaClO_3$ e Na_2SO_4 contains 25.454% of Cl and 36.060% of O. What is the percentage of $NaClO_3$ in the mixture?

3. A mixture of Na_2S, Na_2SO_4 and CH_3COONa weighing 25.19 g, contains 24.29% of S and 21.51% of O. How many grams of CH_3COONa are contained in the mixture?

4. A mixture of CH_4O, C_6H_6 and C_7H_6O weighting 44.37 g gives the elemental analysis: C = 68.74%; H = 8.905%; O = 22.355%. How many grams of C_6H_6 are contained in the mixture? (Cardellini, 1999; p. 90).
5. A mixture contains KClO, $MnCl_2$ and $KMnO_4$. What must the percentage of potassium be to have the chlorine percentage equal to the percentage of oxygen?