THE PROBLEM-SOLVING ABILITY OF HIGH SCHOOL CHEMISTRY STUDENTS AND ITS IMPLICATIONS IN REDEFINING CHEMISTRY EDUCATION

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Abstract

This study investigated the chemistry problem-solving ability of 118 third year students in a public high school. The problem-solving ability of the students was determined using the Chemistry Problem-Solving Ability Test (CPSAT) which the researcher developed. Furthermore, it was found that the CPSAT score can be used to predict chemistry final grade.

Analysis of the scores in each factor reveals that the students performed (a) satisfactorily in Understanding Mathematical Relationships; (b) fairly in Problem Familiarity and Problem Comprehension; and (c) poorly in Applying Specific Problem-Solving Strategies and Using Required Mathematics, Understanding Associated Chemical Concepts, and Understanding Relationships Among Chemical Concepts.

Information on these factors can be used to diagnose difficulties in problem-solving activities in chemistry. Profiling of students' chemistry problem-solving ability is recommended. The scores of an individual student in the different factors will give the teacher invaluable data that may be used to identify the problem areas of the student. In this way, diagnosis and remediation are possible to help the student improve on his/her problem solving ability in chemistry.

Problem-based learning is recommended as an instructional method where students are given real-world problems from which they learn the chemistry concepts. Furthermore, the time allotted for the problem-solving part of topics should be evaluated. There is a need for more class sessions to develop the problem-solving ability of chemistry students.

Introduction

Problem solving is an integral part of any physical science course. Chemistry, being such, involves problem solving. However, most students find the task of solving chemical problems a difficult one. Hence, innumerable studies (*e.g.*, Cohen et al., 2000; Lythcott, 1990; Mason et al., 1997; Nakhleh & Mitchell, 1993) have been conducted to address this problem. Also, extensive work has been done to develop problem-solving ability among students. The reason for such initiative is the fact that problem solving is a higher order cognitive skill that is important in achieving a scientifically literate society. Despite the collective efforts, the need to improve on the problem-solving ability of students still exists. Consequently, there is a need for an assessment instrument aligned with learning goals. All these efforts intend to develop the problem solving ability of students and make them understand the concepts associated with the problems.

It is in this view that the Chemistry Problem-Solving Ability Test was developed and used to assess the problem-solving ability of high school students. This paper presents the assessment made on the problem-solving ability of high school students.

Specifically, answers to the following questions are discussed:

1. What is the relationship between the chemistry problem-solving ability and achievement of high school students?
2. What are the factors underlying chemistry problem-solving ability?
3. What is the problem-solving ability profile of high school chemistry students?
4. What are the implications of the problem-solving ability profile in redefining chemistry education?

Methods and Sample

This study made use of a descriptive design. Factor analysis was utilized to identify the factors underlying the problem solving ability in chemistry. The study described the existing problem solving ability of students in chemistry in terms of: (a) problem comprehension; (b) understanding associated chemical concepts; (c) understanding relationships among chemical concepts; (d) applying specific problem solving strategies; and (e) using required mathematics. Moreover, an analysis of solutions to the problems was done to identify what specific problem-solving strategies were used by the students. In the same manner, the analysis of solutions provided data on the mathematics used by the students.

The study also determined the relationship between chemistry problem-solving ability and achievement of the students. This was done by establishing the predictive validity of the CPSAT using the chemistry final grade as criterion.

Participants in this study were enrolled in a public school of a relatively big enrolment size. For the AY 2002-2003, the school had a population of 5,910 students, of which were 1,599 third year (grade 9) students. One hundred eighteen students comprised the sample of the study. The students ages 14 to 18 consisted of 39 males and 79 females.

Instruments

Chemistry Problem-Solving Ability Test (CPSAT)

The instrument developed in this study is the Chemistry Problem Solving Ability Test (CPSAT). The score of a student in this test was interpreted as his/her problem solving ability. The topics included in the problem solving ability test were: (a) Mole Concept/Stoichiometry; (b) Gas Laws; and (c) Solution Concentrations, which were discussed during the third grading period. In addition, these topics were chosen based on the content or coverage outlined in the Basic Education Curriculum for Chemistry. It is in these topics that competency in problem solving was specified.

The CPSAT consisted of six verbal problems, in which each consisted of three sub-questions. Each sub-question was to assess each of the three factors of chemistry problem-solving ability under study: (a) problem comprehension; (b) understanding relationships among chemical concepts; and (c) understanding associated chemical concepts. Questions on the two remaining factors – applying specific problem solving strategies and using required mathematics – were incorporated in the question on understanding associated chemical concepts. These questions were: “What problem solving strategy did you use in solving the problem?” and “What mathematical concepts and skills did you use in solving the problem?”

Two sample problems are shown in Table 1. Problem 1 is on Stoichiometry/Mole Concept while Problem 2 is on Solution Concentrations.

Table 1
CPSAT sample problems

1. The glowing charcoal that cooks *inihaw na tilapia* and chicken/pork barbecue consists almost entirely of the element carbon. Charcoal burns slowly in oxygen of open air, and the heat given off cooks the food. When charcoal burns in an enclosed space such as a closed room, there may not be enough oxygen to convert the entire carbon-to-carbon dioxide. This is why we grill food over charcoal outdoors – to have a sufficient supply of oxygen.
   a. What is the balanced chemical equation for the reaction of carbon and oxygen?
   b. Based on the balanced chemical equation, give the relationship in terms of the number of moles of carbon and oxygen.
   c. If you are going to use 3 kg of charcoal, how many grams of oxygen will charcoal consume?

   Atomic mass: C=12; O=16
2. Raquel works part-time in a coffee shop. She observed that a typical cup of coffee weighs about 240 g, while a teaspoon of sugar ($C_{12}H_{22}O_{11}$) weighs about 5 g. One day, a customer orders a typical cup of coffee sweetened with two teaspoons of sugar. Raquel calculates for the molarity of the sugar in the cup of coffee in her chemistry class assuming a density of 1.0 g/mL.
   a. What do you have to compute for in the problem?
   b. What is the approximate molarity of sugar in the coffee?
   c. What will happen to the molarity of sugar in the coffee if an additional teaspoon of sugar is mixed to the coffee solution? Why?

   Atomic mass: C=12; H=1; O=16

Problem-Solving Ability Rubric (PSAR)

In scoring the CPSAT, the Problem-Solving Ability Rubric was developed and used. This scoring rubric probed the concepts, strategies and mathematics used by the students in the problem solving process. It also evaluated problem comprehension and understanding of relationships among chemical concepts. A sample of the PSAR used in scoring Problem 2 is presented in Tables 2 and 3.

A corresponding score for the level of performance was given for each solution manifesting specific characteristics of the five factors of problem solving: (a) problem comprehension; (b) understanding relationships among chemical concepts; (c) understanding associated chemical concepts in Table 2; (d) applying specific problem-solving strategies; and e) using required mathematics in Table 3. The maximum number of points per factor was three points. Each problem was given a total of 15 points. Answers were also shown for factors a, b, and c since specific questions that assess them were given.

The PSAR is an adaptation of different rubrics prepared by Foster (2000), Montgomery College Faculty (2002), Montpelier Portfolio Program (2002), National Center for Research on Evaluation (2002), and Tamminga (2002).

Table 2

PSAR for problem 2 (factors a, b and c)

Level of Performance	Problem Comprehension	Understanding Relationships among Chemical Concepts	Understanding Associated Chemical Concepts
	What do you have to compute for in the problem? ▪ The concentration of sugar in the cup of coffee.	What will happen to the molarity of sugar in the coffee if an additional teaspoon of sugar is mixed to the coffee solution? Why? ▪ The molarity will increase since the amount of solute is increased.	What is the approximate molarity of sugar in the coffee? ▪ The concentration of sugar in the cup of coffee is approximately 0.1M.
3	▪ Identifies what is to be computed for in the problem ▪ Supports answer with computation	▪ Solution includes at least 4 relevant relationships among the chemical concepts (e.g. molarity, density, molar mass, solute, solvent, solution) ▪ Gives correct relationship between molarity and amount of solute ▪ Gives correct explanation	▪ Selects and implements the relevant chemical concepts without any conceptual errors (e.g. solutions, solute, solvent, concentration, molarity, molar mass, density, mole)
2	▪ Identifies what is to be solved but fails to give an accurate answer ▪ Does not support answer with computation	▪ Solution includes 3 relevant relationships among chemical concepts ▪ Gives correct relationship between molarity and amount of solute but fails to explain correctly	▪ Evidence that the student has a misconception ▪ Fails to consider a relevant concept needed to solve the problem correctly
1	▪ Fails to give an accurate answer and/or solution to either question ▪ Gives a partially correct answer	▪ Solution includes 1 or 2 relevant relationships among chemical concepts ▪ Fails to give correct relationship between molarity and amount of solute	▪ Evidence that the student has several misconceptions ▪ Fails to consider several relevant concepts needed to solve the problem correctly
0	▪ Nothing written ▪ Complete misunderstanding of the problem ▪ Only repeats information in the problem	▪ Nothing written ▪ Fails to give correct relationship	▪ Nothing written ▪ Only repeats information in the problem ▪ Gives a wrong answer and fails to show solution

Table 3

PSAR for problem 2 (factors c and d)

Level of Performance	Applying Appropriate Problem Solving Strategies	Using Appropriate Mathematics
3	▪ Selects and implements appropriate strategy (e.g. breaking the problem into steps, identifying sub-goals, ratio and proportion, dimensional analysis) needed to solve the problem ▪ Solution progresses from goal (e.g. molarity of sugar) to general concepts (e.g. molar mass, density) to answer (e.g. 0.1M)	▪ Mathematics is correct; numbers are either substituted at each step or at the last step ▪ Demonstrates understanding through consistent use of mathematical language (e.g. number sense, number relationships, operations, algebra, or arithmetic).
2	▪ Fails to carry out the strategy far enough (e.g. computation only up to mole sucrose) ▪ Plan could gave led to a correct solution if implemented properly	▪ Sparse use of language (e.g. number sense, number relationships, operations, algebra, or arithmetic). ▪ Solution violates mathematics rules (e.g. algebra, arithmetic).
1	▪ Solution does not proceed past basic statement of concepts (e.g. solute, solution) ▪ Partially correct plan based on part of the problem being interpreted correctly	▪ Solution terminates for no apparent reason. ▪ When an obstacle is met, "math magic" or other unjustified relationships occur. ▪ When an obstacle is met, solution stops. ▪ Serious math errors.
0	▪ Nothing written ▪ Difficult to assess ▪ Selects a totally inappropriate strategy	▪ Nothing written. ▪ Used no mathematical language beyond problem statement or consistently used inappropriate or inaccurate math language to communicate his/her solution.

Results and Discussion

Chemistry Problem-Solving Ability and Achievement

The predictive validity of the CPSAT was established using the chemistry final grade as criterion. Results show that the CPSAT score is a positive significant predictor of chemistry final grade. This means that the CPSAT score can be used to predict chemistry final grade, which is the measure of achievement in chemistry. A higher CPSAT score results in a higher final grade in chemistry.

Factors Underlying Chemistry Problem-Solving Ability

Factor analysis was performed to determine the factors underlying the chemistry problem-solving ability. This statistical procedure aimed to establish that the five factors targeted by the 30 sub-questions in the CPSAT are indeed the factors of chemistry problem-solving ability. For this study, N=118; hence, a factor loading of ±.500 was considered significant (Hair et al., 1998). Factor analysis on the 30 variables (sub-questions) identifies the following as factors underlying chemistry problem-solving ability:

1. Problem Familiarity in Gas Laws (Factor 1)
2. Understanding Concept of Molarity (Factor 2)
3. Understanding Concept of Excess and Limiting Reagents (Factor 3)
4. Understanding Mole Concept (Factor 4)
5. Problem Familiarity in Solution Concentration (Factor 5)
6. Applying Specific Problem-Solving Strategies and Using Required Mathematics (Factor 6)
7. Problem Comprehension (Factor 7)
8. Understanding Mathematical Relationships (Factor 8)
9. Understanding Relationships Among Chemical Concepts (Factor 9)

However, the nine factors are reduced to six: (a) Problem Familiarity; (b) Understanding Associated Chemical Concepts; (c) Applying Specific Problem-Solving Strategies and Using Required Mathematics; (d) Problem Comprehension; (e) Understanding Mathematical Relationships; and (f) Understanding Relationships Among Chemical Concepts. Factors 1 and 5 were grouped together since both were on problem familiarity differing only on the topic. Similarly, Factors 2, 3, and 4 were grouped together.

Problem Familiarity

Raw scores in the CPSAT reveal that as compared to other problems, the students got higher scores on the two problems on gas laws. This indicates that the students are familiar with gas law problems. It is inferred that students were very much exposed to this type of problems in the classroom. On the other hand, it was found that students were not familiar with the five sub-questions on solution concentration. Analysis of the problems reveals that these are not typical textbook verbal problems, and students are not familiar with such problem structure. Hence, Problem Familiarity refers to students being familiar or not familiar with the given verbal problems.

Understanding Associated Chemical Concepts

Understanding Associated Chemical Concepts is the ability of students to understand and apply the associated concepts (on mole/stoichiometry, gas laws, and solution concentrations) to the problem. It involves selection and implementation of relevant chemical concepts without any misconceptions.

Applying Specific Problem-Solving Strategies and Using Required Mathematics

Applying Specific Problem-Solving Strategies involves the ability to select and implement a strategy that shows how the solution progresses from goal, to general concepts, to answer. On the other hand, Using Required Mathematics accounts for a student's mathematical skill as applied to the specific problem. It probes the solution to the problem in accordance with mathematical (*e.g*., algebraic and arithmetic) rules. It also involves demonstration of understanding through consistent use of mathematical language.

Problem Comprehension

Problem Comprehension refers to the ability to understand the problem by extracting and interpreting meaning from an expression or message. It involves translation of chemical names to symbols, identifying variables to be solved or relevant variables needed to solve the problem, and considering constraints in the problem. For instance, question *a* of Problem 1 in Table 1 requires problem translation where students are required to translate chemical names to chemical symbols as they search for meaning and solution (Sayward, 1980).

Understanding Mathematical Relationships

Understanding Mathematical Relationships refers to the ability to understand and apply relationships among numbers. In this study, sub-questions on gas laws required students to determine the effect on the volume of the bubble if the pressure is quadrupled and the temperature is halved. It is inferred that students would not be able to solve the problem correctly even if they know the concept behind the Combined Gas Law if they did not understand what is meant by *pressure is quadrupled* and *temperature is halved*.

Understanding Relationships Among Chemical Concepts

Understanding Relationships Among Chemical Concepts refers to the ability to relate concepts involved in the problem. The concepts or quantities may be directly or indirectly stated in the problem. It is measured in terms of the number and correctness of relevant relationships among the chemical concepts. Sub-questions in the CPSAT measured understanding of stoichiometric relationships, inverse proportionality, and causal relationship.

Qualitative Analysis on Students' Solutions

Qualitative analysis on the solutions shows that the problem-solving strategies used by the students were: (a) guessing and testing; (b) writing an equation; (c) ratio and proportion; (d) breaking the problem into steps; (e) factor method; (f) constructing a table; and (g) word solution. In guessing and testing, the students just manipulated the given values, the reason for which was not clear. There were students who get the correct answer but the solution was wrong. This suggested that they were guessing.

Similarly, the analysis of the solutions revealed descriptions on the mathematics of some students such as: (a) solution violates mathematics rules (*e.g*., algebra, arithmetic); (b) solution terminates for no apparent reason; and (c) solution stops when an obstacle is met.

Student Performance in Each Factor

To further evaluate the factors underlying chemistry problem-solving ability, the mean score for each factor was computed, and a scoring scheme was developed. Table 4 shows the Chemistry Problem Solving Ability (CPSA) Factors, and the maximum possible score, the mean score, and the percentage score for each factor. The mean CPSAT score was 18.38, which was 20.4% of the 90 points maximum score.

Table 4
CPSA factors, number of items, maximum possible score, mean score, and percentage score for each factor

CPSA Factor	Number of Items	Maximum Possible Score	Mean Score	Percentage Score
Problem Familiarity	12	36	10.81	30.0
Understanding Associated Chemical Concepts	9	27	1.21	4.5
Problem Comprehension	3	9	2.95	32.8
Applying Specific Problem Solving Strategies and Using Required Mathematics	2	6	0.02	0.3
Understanding Mathematical Relationships	2	6	2.75	45.8
Understanding Relationships Among Chemical Concepts	2	6	0.64	10.7
Total	30	90	18.38	

The scoring scheme in Table 5 used to interpret students' performance in each factor revealed that the students performed poorly in the CPSAT.

Table 5
Scoring scheme for interpreting students' performance in each factor and in the CPSAT

Percentage Score	Interpretation
81-100	Outstanding
61-80	Very Satisfactory
41-60	Satisfactory
21-40	Fair
0-20	Poor

The low mean score of the research sample may be attributed to the following reasons:

1. A significant number of students did not answer some of the test items.
2. Students may have already forgotten the topics covered by the CPSAT since these topics were taken during the third grading period, and the CPSAT was administered during the end of the fourth grading period.
3. Students may have lacked exposure to the type of problems encountered in the CPSAT.

4. The time allotted to the discussion of the problem solving part of mole concept/stoichiometry, gas laws, and solution concentration may have not been thorough enough for the students to acquire the necessary concepts and skills needed to be able to solve problems.

5. Students may have not been comfortable with the English language used in writing the verbal problems.

Using Tables 4 and 5, the performance of the students in each factor was evaluated. Analysis of the scores revealed the following regarding students' performance in the factors underlying problem solving ability:

1. The students performed satisfactorily on Understanding Mathematical Relationships.
2. The students performed fairly in Problem Familiarity and Problem Comprehension.
3. The students performed poorly in Applying Specific Problem Solving Strategies and Using Required Mathematics; Understanding Associated Chemical Concepts; and Understanding Relationships Among Chemical Concepts.

It is noteworthy that the students performed poorly on two factors—Understanding Associated Chemical Concepts and Understanding Relationships Among Chemical Concepts—that are considered the bases of problem solving in chemistry. According to Chekuri (1997), the purpose of problem solving is for students to understand the relationships among the physical quantities involved in a phenomenon that leads to an understanding of the phenomenon itself. For example, to be able to understand Boyle's Law (which states that the volume of a fixed amount of gas at constant temperature is inversely proportional to the pressure), the students should be able to understand the relationship between the physical quantities volume and pressure. If the inverse proportionality relationship of volume and pressure is not understood, then the concept of Boyle's Law is also not understood. Clearly, the result of the CPSAT revealed that the objective of problem solving was not achieved.

Conclusions and Implications

Given the results of factor analysis on the Chemistry Problem-Solving Ability Test (CPSAT) and the analysis of the scores in each factor, the implications in redefining chemistry education are hereby noted.

The construct of chemistry problem-solving ability suggests a need to reorient the teaching of chemistry at the high school level. Emphasis on understanding associated chemical concepts and relationships among them is suggested. This necessitates the use of analogies and graphic organizers like concept maps and schematic diagrams. However, the teaching of chemistry problem solving should not only focus on quantitative problem solving. Equal attention should be given to conceptual problem solving. This will provide a more holistic approach to teaching problem solving in chemistry.

Problem solving is synonymous to mathematics for problem solving entails mathematical knowledge and skill. Therefore, the use of required mathematics and understanding of mathematical relationships are important in chemistry problem solving. The teaching of problem solving in chemistry requires emphasis on chemical-mathematical skills (*e.g*., ability to isolate ratio, using logarithmic laws, ability to deal properly with exponents, roots and scientific notation, and ability to make proper approximations). Furthermore, the finding that the students performed poorly in using required mathematics suggests that mathematics as a separate subject be taught properly, and be appreciated both by teachers and students. In relation to chemistry problem solving, students should have a considerably strong foundation in number sense, number relationships, arithmetic and algebra.

The finding that the students performed poorly on applying specific problem-solving strategies suggests that despite more than 60 different problem-solving strategies described in literature (Woods, 1989; as cited in Noh & Scharmann, 1997), the students still cannot perform the basic steps of the procedure. Applying specific problem-solving strategies by itself is a skill. What makes it more difficult for the teacher to teach problem solving in chemistry, just like in mathematics, is that the use of a problem-solving strategy requires other problem-solving skills such as defining the problem, identifying pertinent information and variables, combining separate pieces of information, and evaluating the solution (Ashmore, Frazer, & Casey, 1979; in Asieba & Egbugara, 1993).

Qualitative analysis on students' solutions reveals that two of the problem-solving strategies used are factor [label] method (or dimensional analysis) and ratio [and proportion] method. These two are the most popular methods used in high school chemistry problem solving. This is primarily so because textbooks generally make use of these two methods. As a consequence, teachers present quantitative problem solving using dimensional analysis and ratio method. Considering this, there seems to be an urgent need to diversify the problem-solving teaching approach used not only by chemistry teachers, but also by textbook writers.

Problem familiarity is one factor that contributes to the problem-solving ability of students in chemistry. The students' performance in problem familiarity shows that the students lack exposure on word problems. This implies that the time allotted by the Department of Education Basic Education Curriculum for Chemistry for the problem solving part of topics like Stoichiometry/Mole Concept, Gas Laws and Solution Concentration is not sufficient. The context of the problem also contributes to problem familiarity. Word problems that are more contextual and experiential illustrating real-life problem situations are more relevant to the students.

Problem comprehension in this study refers to the ability to understand the problem by extracting and interpreting meaning from an expression or message. Considering this, there is a need to strengthen language proficiency in English, among teachers and students since it is the medium of instruction in chemistry, and chemistry textbooks are written in English.

In addition, problem comprehension involves translation of chemical names to symbols, identifying variables to be solved or relevant variables needed to solve the problem, and considering constraints in the problem. Therefore, with this and the preceding discussion of the other factors, it appears that the six factors underlying chemistry problem-solving ability are interrelated and the implication of one for chemistry education affects the implication of the others. Hence, it is necessary that all factors be developed as specialized skill to develop the chemistry problem-solving ability of the students.

Recommendations for Teachers

The scores of an individual student in the different factors will give the teacher invaluable data that may be used to identify the problem areas of the student. In this way, diagnosis and remediation are possible to help the student improve on his/her problem-solving ability in chemistry.

A sample student (Student #28) profile is shown in Figure 1. At this point, the raw and percentage scores of the student may only be compared with the raw and percentage scores of the research sample. This will give the student profile, where the scores of the student are plotted against CPSA factors, and compared with the scores of the research sample.

The sample profile shows that Student #28 generally performed better as compared to the research sample. Student #28 got a higher score than the research sample in the CPSAT, and in five out of the six CPSA factors. It was only in Strategies and Mathematics that Student #28 and the research sample had approximately equal score (*i.e.*, 0 and 0.02, respectively).

In the CPSA factors, Student #28 performed poorly in understanding concepts, and strategies and mathematics; satisfactorily in problem comprehension, and understanding relationships; very satisfactorily in problem familiarity; and outstandingly in mathematical relationships. Student #28 performed satisfactorily in the CPSAT.

CHEMISTRY PROBLEM SOLVING ABILITY TEST
STUDENT REPORT

Name: Student #28 Age: 15 Sex: Female

School: Marikina High School Year Level: Third Year Test Date: March 28, 2003

CPSA Factors	Maximum Possible Score	Raw Score	Class Mean Score
Problem Familiarity	36	26	10.81
Understanding Concepts	27	3	1.21
Problem Comprehension	9	4	2.95
Strategies and Mathematics	6	0	0.02
Mathematical Relationships	6	5	2.75
Understanding Relationships	6	3	0.64
Total	90	41	18.38

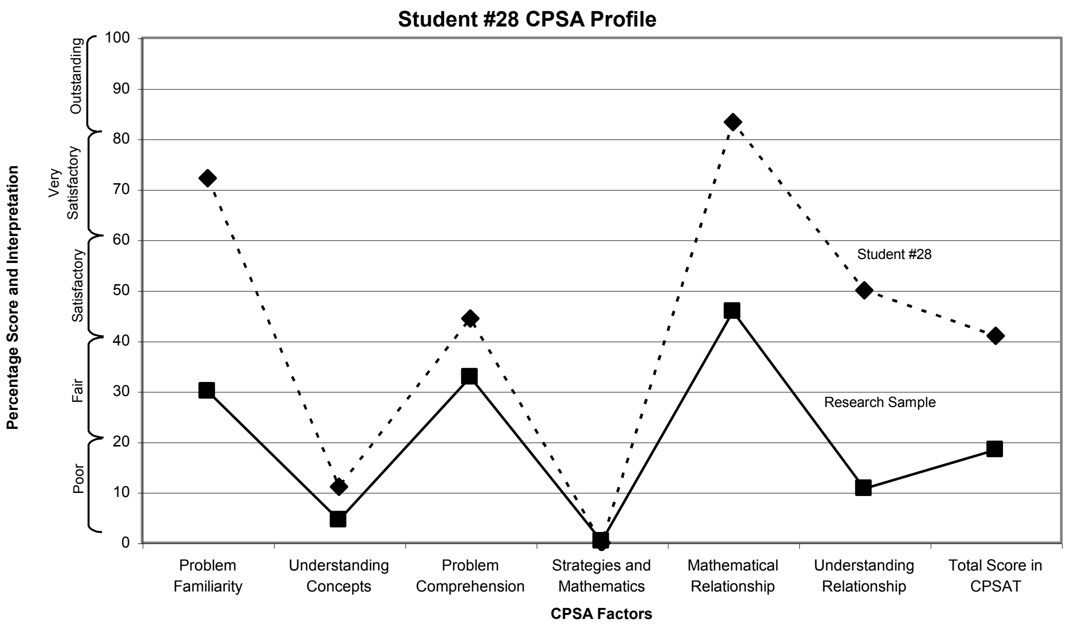

Figure 1. Sample Student Profile on Chemistry Problem Solving Ability

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