Identifying Deficiencies in Engineering Problem Solving Skills

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Introduction:

Problem solving is a complex multistep process that leads to finding a feasible solution to a problem. Engineering students must master the skills of problem solving to be able to succeed in an intense problem solving curriculum, as well as in the workplace. The engineering curriculum exposes students to different types of problems, most of them well defined. Once in the workplace, engineering problem solving for the most part involves ill-structured problems solved using diverse methods [1-3].

Most problems in engineering are graded using a rubric that accounts for the solution, and not for the thought process. The simplicity of those rubrics does not permit the identification of deficiencies in problem solving skills. In this project, a problem solving rubric developed for Physics students was adapted to assess the problem solving skills of engineering students enrolled in a first semester engineering course. Unlike most rubrics used in engineering courses, this rubric grades the thought process, and splits the problem solving approach into separate categories: Useful Description, Engineering and Math Approach, Application of Engineering, Mathematical Procedures, and Logical Progression. In this project, the rubric was implemented to identify deficiencies in problem solving in first year non-calculus ready students enrolled in an engineering curriculum.

Methodology:

A. Problem Solving, Skills Required, and Rubrics Available to Assess Problem Solving

Problem solving uses high-level reasoning to analyze problems, to assess potential solutions, and to find an appropriate answer. To solve math and engineering problems, students must be able to comprehend the problem, must identify methods to solve the problem, must select the appropriate equations, concepts and information to solve the problem, must be able to follow an appropriate mathematical procedure, and once a solution is found, must be able to assess if the solution found is appropriate.

Expert problem solvers view a problem from a conceptual perspective and are able to identify patterns of information in the problem that novices are unable. Experts have a great deal of content knowledge and are capable of retrieving information from memory with little attentional effort. They organize the information based on core concepts and their thinking reflects a deep understanding of the subject. Experts also show a flexible approach to solving new problems [4].

Contrarily, novice problem solvers tend to see problem solving as memorizing, recalling and manipulating equations to find an answer. Novice problem solvers tend to observe problems in terms of numbers and calculations, like a series of isolated information and equations relevant to the problem [4].

A number of rubrics have been developed to assess problem solving skills in students. Parematasari and colleagues implemented a 4 indicator problem solving rubric based on: Identification of the Problem, Planning a Solution, Implementing a Solution, and Evaluation [5].

The rubric, which implemented a 1-4 scoring scale, was tested in a Physics class with senior high school students. Another rubric implemented in Physics uses 44 sub-skills split in three categories: knowledge, beliefs, expectations and motivations, and processes [6]. That rubric was used to evaluate problem solving skills in students enrolled in courses College Algebra to Introductory Calculus. Many other problem solving rubrics are available [7].

B. Assessment of Problem Solving Skills in Freshman Engineering Students Enrolled in College Algebra

1. Characteristics of students participating in the study

Forty first-year engineering students enrolled in a Land-grant institution in the mid-Atlantic region participated in this study. Most of the participants in the study are male (82.5% male; male=33, female=7). All students participating in the study were enrolled in College Algebra at the time of the study.

2. Assessment of Problem Solving Skills

For this study, four problems were selected and analyzed from a test used to assess students' ability to solve engineering and mathematical problems. Those four problems were selected since they represent concepts that the students should have mastered at the end of the semester when the test was administered. Also, since the goal was to check the applicability of the rubric to assess engineering problem solving skills, we avoided problems that were more complex and required more steps. Those complex multi-step problems are currently being analyzed and their results are not included in this paper.

The four questions analyzed and included in this paper were:

Question 3 (equation of a line): A model rocket is fired in a vertical plane and the velocity v(t) is measured as shown in the following figure:

V(t) [m/s]	T [s]
34.3	0.5
19.6	2.0

The velocity satisfies the equation $v(t)=v_o+at$, where v_o is the initial velocity in m/s and a is the acceleration in m/s^2.

Find the equation of the line v(t) and determine both the initial velocity v_o and the acceleration a.

Question 4 (circle geometry): A circular summing pool, 20 feet in diameter, is enclosed by a white wooden deck that is 3 feet wide. What is the area of the deck? How much fence is required to enclose the deck?

Question 6 (writing algebraic equation): Tommy grossed $435 one week by working 52 hours. His employer pays time-and-a-half for all hours worked in excess of 40 hours. Set up an expression and determine Tommy's hourly wage.

Question 8 (mixture problem): A coffee manufacturer wants to market a new blend of coffee that sells for $3.90 per pound by mixing two coffees that sell for $2.75 and $5.00 per pound, respectively. What amounts of each coffee should be blended to obtain the desired mixture? Assume that the total weight of the desired blend is 100 pounds.

3. Description of the Rubrics Used to Evaluate Problem Solving Skills

Table 2. Rubric Created to Assess Problem Solving Skills (adapted from Docktor et. al [8-9])

Topic	Topic Description	Rubric/SCORE
Useful Description	Student organizes given information into an appropriate and useful representation either symbolically, visually, or in writing	5 –useful, appropriate, and complete 4 – useful, but minor omissions or errors 3 – parts aren't useful and/or contain errors 2 – most isn't useful and/or contain errors 1 – entire description isn't useful and/or contains errors 0 – no description included when one is necessary
Math and Engineering Approach	Student selects appropriate concepts and principles (general ideas) to solve the problem	5 – appropriate, and complete 4 – minor omissions or errors 3 – parts are missing and/or inappropriate 2 – most is missing and/or inappropriate 1 – all concepts and principles are inappropriate 0 – no approach indicated when it is necessary
Specific Application of Math and Engineering	Student can apply the general approach to the specifics of the problem in the form of definitions, qualitative relationships, equations, initial conditions, and assumptions	5 – appropriate, and complete 4 – minor omissions or errors 3 – parts are missing and/or contain errors 2 – most is missing and/or contain errors 1 – entire specific application is inappropriate and/or contains errors 0 – no application provided when it is needed
Mathematical Procedures	Student correctly executes mathematical procedure	5 – appropriate, and complete 4 – minor omissions or errors 3 – parts are missing and/or contain errors 2 – most is missing and/or contain errors 1 – entire procedure is inappropriate and/or contains errors 0 – no mathematical procedure provided when it is needed
Logical Progression	Student's process stays focused on the goal of the problem, has a coherent order, and the reasoning can be understood.	5 – clear, focused, logically connected 4 – minor inconsistencies 3 – parts are unclear, unfocused, or inconsistent 2 – most is unclear, unfocused, or inconsistent 1 – entire progression is unclear, unfocused, or inconsistent 0 – no evidence of logical progression when it is necessary

In order to assess students' math and engineering problem solving skills, a rubric was developed breaking down the problem solving process into five categories: Useful Description, Math and Engineering Approach, Specific Application of Math and Engineering, Math Procedures, and Logical Progression. These categories were chosen based on their successful implementation by Docktor et. al in their analysis of students' written problem solving skills in introductory physics courses [8-9]. Each category was scored on a scale from 0 to 5 with 0 being the worst possible score and 5 being the best. The final rubric is presented in Table 2.

In order to simplify the rubric and ensure its appropriate application, the descriptions of each score were kept similar between categories. A score of 0 given in any category is awarded when no work has been presented for that category when it was needed for the student to solve the problem. A score of 1 through 4 given shows that the category has been presented, but the work is either (1) entirely inappropriate, (2) mostly inappropriate or missing, (3) partially inappropriate or missing, or (4) mostly complete and appropriate, but with minor errors or oversights. A score of 5 is awarded when all work presented for the category is both appropriate and complete.

In addition to the 0 to 5 scale, two designations were created in the case that a category was not applicable and thus did not require a score. The designation NAP stands for “Not Applicable to the Problem” and was used for a category that was not necessary in order to solve the problem. Most frequently, this is used for the Useful Description category for problems where the table or diagram was already provided in the problem and did not need to be created by the student. The second designation, NAS, stands for “Not Applicable to the Solver”. This designation is used in order to avoid penalizing a student for not showing work that was not necessary for them to solve the problem. An example of this would be if a student did not draw a diagram but was still able to create correct equations and solve the problem without one. It could also be used in the event that a student does not show the individual steps of their mathematic procedure but was able to correctly solve the problem without showing the extra work. As students grow more confident in their problem solving ability, they will often begin to skip intermediate steps in the same way an expert problem solver would, and this should not be penalized if it has no negative affect on their ability to correctly solve the problem. The difference between a score of NAS and a score of 0 is that NAS is only given when the student was still able to solve the problem correctly. If the student solves the problem incorrectly, a 0 should be given because these steps were necessary for them to correctly understand and/or solve the problem.

The first category assessed by the problem solving rubric, Useful Description, describes the students’ ability to take the information provided in the problem and organize it in a way that helps to solve the problem. This could take a number of forms, including a diagram, a table, a written explanation of the problem, or any other way of organizing the information that helps the student to better understand the problem. The description may, but is not required to include information such as drawing a physical representation of the problem, stating knowns and unknowns, assigning variables to specific quantities, assumptions, or stating the goal of the problem. The requirements for the description will be based on the problem and the method chosen by the student to solve it. The key to this category is that the representation must be useful as well as accurate. This means that the student should use the description as a means to work towards their solution.

The next category, Math and Engineering Approach, encompasses the ability for the student to select the necessary concepts and general ideas needed to solve the problem. For instance, when given two points and asked to form a linear equation, the student may identify the concept of slope and intercept as two necessary pieces of information in order to come to the solution. Other general ideas may include the need for two equations to solve for two unknowns, applicable theorems such as Pythagorean theorem to solve right triangle problems, or any other concept that will assist in reaching the answer to the problem. This category does not require the correct application of the concepts, but the recognition that they are necessary.

The Specific Application of Math and Engineering category is used to assess the students' ability to apply the necessary concepts to the solution of the problem. This section can include defining equations or qualitative relationships between quantities, assumptions, constraints, initial conditions, or any other information specific to the problem being solved.

Mathematical Procedures is used to analyze the students' ability to solve the equations and relationships from the Specific Application of Math and Engineering section using basic mathematical rules in order to obtain the desired answer to the problem. This can include basic order of operations, algebra to rearrange, simplify, or substitute values, as well as the "guess and check" method.

The final category, Logical Progression, represents the students' ability to organize their thoughts in a coherent order, work consistently, and stay focused on the problem at hand. While the logic for each step need not be explicitly stated, the thought process of the student should be evident in the work provided and each step should consistently work towards the goal of solving the problem. The answer to the problem should also be consistent with students' knowledge of nature (for instance, that percentages of a mixture should add to 100%).

The scoring for each category is based on the consistency from one section to the next. For example, if a student does not correctly form the necessary equations in the Specific Applications section, the Mathematics Procedure score is based on the ability of the student to solve the incorrect equation they provided, rather than the correct equation. This is done to avoid penalizing students for a single mistake more than once in the problem.

C. Statistical Analysis of Data

A linear regression model was used to understand the relationship between students' test scores and the scores obtained using the problem solving rubric. The statistical software SPSS was utilized to analyze the data. Statistical significance was determined using a p-value less than 0.05. This study was reviewed and approved by the West Virginia University Institutional Review Board.

Results:

Although different rubrics have been implemented to assess students' problem solving skills, some of those rubrics are not practical for the purpose of this study. Since the data include information from more than 30 students, a rubric that contains too many indicators will be impractical for use. Another issue we found with other rubrics was that they were too simplistic and could not properly assess problem solving skills.

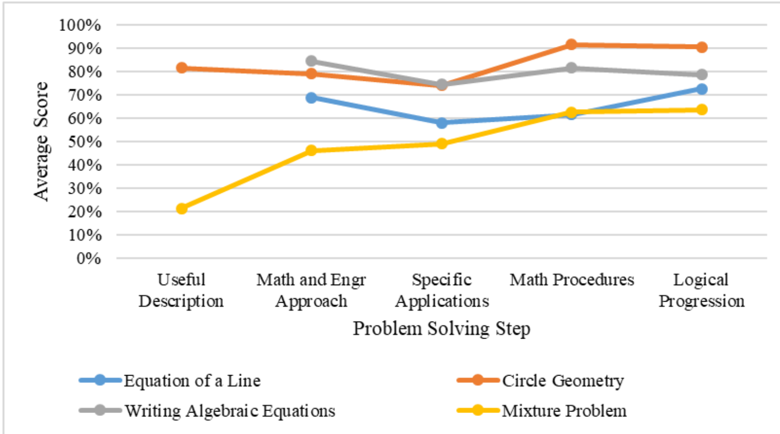

Figure 1. Average Problem Solving Skill Proficiencies for Each Examined Question

The results from the study, shown above in Figure 1 were found to vary based on question type. Students performed the best in problems in which the student did not need to develop the equation to use to solve the problem. An example of such a problem is the Circle Geometry problem, in which students were asked to find the area and circumference of a circular deck surrounding a circular pool. The equations for area and circumference are standard and typically memorized by the students, and there was no need for them to develop a complex equation to solve the problem. As a result, problem solving scores were generally high in all categories.

For problems in which students had to develop the equation, students were found to have issues devising an appropriate equation, which corresponds to the "Specific Applications of Math and Engineering skill" section of the rubric. The Equation of a Line problem, where students were given two points and asked to find the linear equation connecting the two, as well as the Mixture Problem, where students needed to create two equations to solve for the weights of two different nuts in a mixture, proved particularly difficult. The Mixture Problem's challenges were compounded by students' inability to recognize the need for two equations, rather than one, to correctly solve the problem. While many students were unable to create the appropriate equation(s) to solve these problems, once they decided on an equation, whether right or wrong, students were able to follow the appropriate mathematical procedure to solve their equation and find a solution to the problem. It was also noted that not being able to properly identify the correct math and engineering approach made them stop trying to solve those problems.

The Writing Algebraic Equations problem does not follow the same trend of low scores as the other two equations development problems. While there is still a deficit in the students' ability to design an equation capable of solving the problem, some students were able to overcome this deficit by taking a different Math and Engineering Approach. This problem involved determining a worker's hourly pay rate from their total paycheck and the number of regular and overtime hours worked, assuming overtime paid 1.5x. The concept of this problem was simple enough that some students were able to employ a "Guess and Check" method and correctly solve the problem without developing an equation. This boosted the scores for this question, separating it from the other equation development questions.

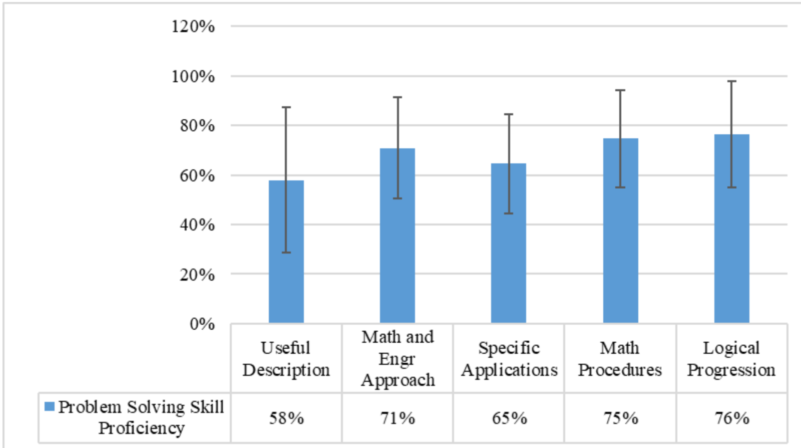

Figure 2. Average Problem Solving Skill Proficiency

The average scores for each step in the problem solving process are shown in Figure 2. In general, it was found that students tend to skip steps in their problem solving approach. Among all questions, the Useful Description category had the lowest score, because students skipped this step in the solution of the problem. While those who created a description generally scored very well, a majority of students received a score of 0 for the category, significantly lowering the average. In addition, two of the questions, questions 3 and 6, did not require students to provide Useful Description to solve the problem. For these questions, all students received an NAP, which does not contribute to the average score.

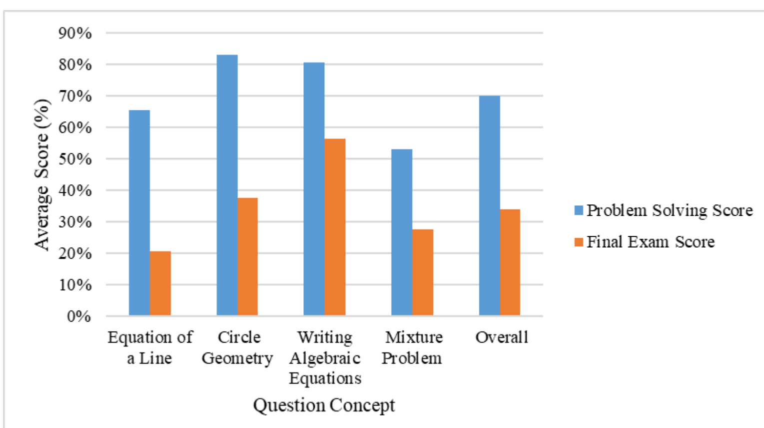

Figure 3. Average Problem Solving Score and Average Final Exam Score for Each Question

The scores obtained using the rubric were higher in comparison with the actual test scores because the rubric accounts for students' written (thinking) process as seen in Figure 3. Throughout the analysis of the exams, a number of students were found to have made a simple error in setting up the problem that led to an incorrect solution, but generally showed the correct problem solving process. These students received zero credit for their work on the exam because the answers weren't precisely what was provided in the solution but received relatively high problem solving scores for their process because their single error was not compounded through the scoring of the entire rubric. Despite the discrepancy in test score vs problem solving score, as Figure 4 shows, there was a linear relationship between rubric scores and test scores, with significance found in both slope and intercept for the regression line (p-value <0.05).

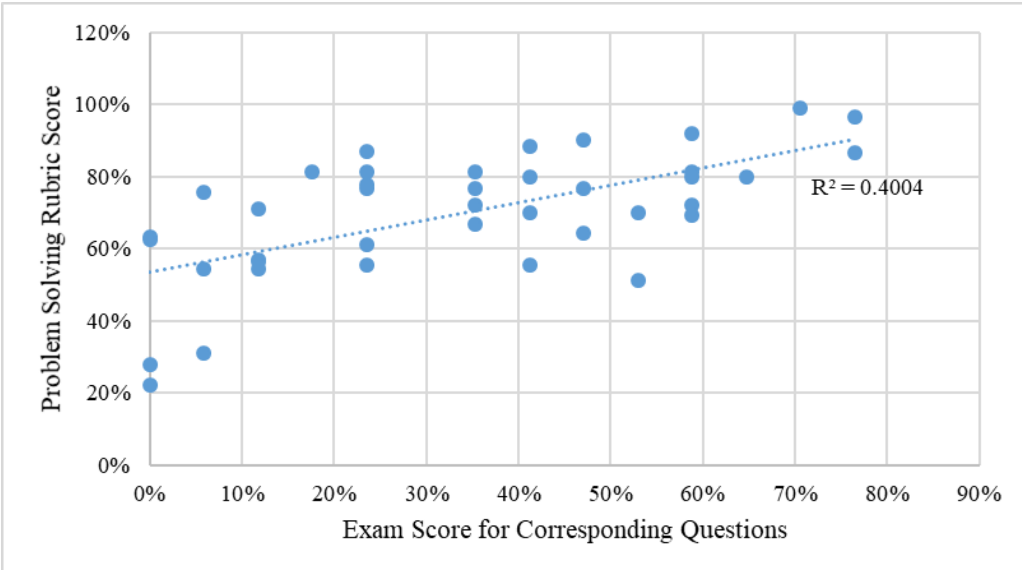

Figure 4. Comparison of Overall Problem Solving Score to Exam Score (p-value <0.05)

Discussion:

Students at the College Algebra level have deficiencies in knowledge that calculus-ready students do not have. These students' deficiencies in knowledge are reflected by their inability to combine given information to form equations capable of solving engineering and mathematics problems. This skill is vital to any engineer, regardless of discipline, and will require significant training in order to successfully retain these students within engineering.

At this point in the study, we have applied the rubric in order to verify its effectiveness at quantifying students' problem solving skills in the desired five categories. In order to analyze the rubric more in depth, we plan to expand the study to include problems with higher complexity and a larger sample size.

Acknowledgements:

The authors would like to thank Dr. Melissa Morris for assisting in the development of engineering and math problems for the study. This material is based upon work supported by the National Science Foundation (NSF) under Grant number DUE-1504730. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

References:

[1] Jonassen, David. "Supporting problem solving in PBL." *Interdisciplinary Journal of Problem-Based Learning* 5.2 (2011): 95-119.

[2] Jonassen, David H. "Toward a design theory of problem solving." *Educational technology research and development* 48.4 (2000): 63-85.

[3] Jonassen, David H. "Instructional design models for well-structured and III-structured problem-solving learning outcomes." *Educational technology research and development* 45.1 (1997): 65-94.

[4] Ali, Marlina, Corrienna Abdul Talib, and Norulhuda Ismail. "An overview of research on expert and novice problem solvers in Physics." (2015).

[5] Permatasari, Arum Karima, Edi Istiyono, and Heru Kuswanto. "Developing Assessment Instrument to Measure Physics Problem Solving Skills for Mirror Topic." *International Journal of Educational Research Review* 4.3 (2019): 358-366.

[6] Adams, Wendy K., and Carl E. Wieman. "Analyzing the many skills involved in solving complex physics problems." *American Journal of Physics* 83.5 (2015): 459-467.

[7] Nikat, Rikardus Feribertus, and Eny Latifah. "The evaluation of Physics students' problem solving ability through MAUVE strategy (magnitude, answer, units, variables, and equation)" *PEOPLE: International Journal of Social Sciences* 3.3 (2017).

[8] Docktor, Jennifer, and Kenneth Heller. "Robust assessment instrument for student problem solving." *Proceedings of the NARST 2009 Annual Meeting, Garden Grove, CA*. (2009).

[9] Docktor, Jennifer L., et al. "Assessing student written problem solutions: A problem-solving rubric with application to introductory physics." *Physical review physics education research* 12.1 (2016): 010130.