



Connections between Undergraduate Engineering Students' Problem Solving Strategies and Perceptions of Engineering Problems

Catherine D. McGough, Clemson University

Catherine McGough is currently a graduate research assistant in Engineering and Science Education at Clemson University. She obtained her B.S. in Electrical Engineering from Clemson University in 2014. Her research interests are in undergraduate engineering student motivations and undergraduate engineering problem solving skill development and strategies.

Adam Kirn, University of Nevada, Reno

Adam Kirn is an Assistant Professor of Engineering Education at University of Nevada, Reno. His research focuses on the interactions between engineering cultures, student motivation, and their learning experiences. His projects involve the study of student perceptions, beliefs and attitudes towards becoming engineers, their problem solving processes, and cultural fit. His education includes a B.S. in Biomedical Engineering from Rose-Hulman Institute of Technology, a M.S. in Bioengineering and Ph.D. in Engineering and Science Education from Clemson University.

Courtney June Faber, Clemson University

Courtney Faber is a graduate student in the Department of Engineering and Science Education at Clemson University and a National Science Foundation Graduate Research Fellow. She holds a B.S. in Bioengineering from Clemson University and a M.S. in Biomedical Engineering from Cornell University.

Dr. Lisa Benson, Clemson University

Lisa Benson is an Associate Professor of Engineering and Science Education at Clemson University, with a joint appointment in Bioengineering. Her research focuses on the interactions between student motivation and their learning experiences. Her projects involve the study of student perceptions, beliefs and attitudes towards becoming engineers and scientists, and their problem solving processes. Other projects in the Benson group include effects of student-centered active learning, self-regulated learning, and incorporating engineering into secondary science and mathematics classrooms. Her education includes a B.S. in Bioengineering from the University of Vermont, and M.S. and Ph.D. in Bioengineering from Clemson University.

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Introduction

Due to its central role in educating future engineers, problem solving is of great interest in engineering education research. Problem solving instruction has been approached in methodical ways for decades^{1,2}; however, engineering education is still lacking a more personalized approach to problem solving instruction. Students' problem solving skills could be improved through the use of highly individualized problems tailored to each student's particular aptitudes and interests. Students' interests are largely driven by their motivation³. This personalized approach to teaching effective problem solving is crucial for the next generation of engineering and science educators⁴. By recognizing the differences in students' motivations and how it affects their problem solving approaches, more personalized instruction could be achieved.

Different aspects of motivation and problem solving have been explored; previous research identified connections between how students' perceive the future students' and their metacognition during solving an open-ended engineering problem⁵. Another study identified connections between how students' perceive engineering problems and how they perceive the future⁶. Due to these findings, we hypothesize that there may also be a connection between students' problem solving strategies and students' perceptions of the future; this hypothesis lead to the research question: How are engineering students' motivations, as characterized by their perceptions of the future, influencing their problem solving processes on unfamiliar problems? To answer this question, this paper combines outcomes of a prior study of students' perceptions of the future⁶ with a study on problem solving strategies. A description of how strategies are identified using student's written work and audio reflections will be included to promote future work in problem solving research.

Theoretical Frameworks

Problem Solving Strategies

Although there are many frameworks in place for problem solving strategies, for the context of sophomore and junior level engineering students we selected Nickerson's framework as the most applicable⁷. Previous research indicates that Nickerson's framework of problem solving strategies are applicable to undergraduate engineering students' problem solving approaches⁸. Nickerson divides problem solving strategies into nine types: subgoaling, working backwards, hill climbing, means-end analysis, forward chaining, considering analogous problems, specialization and generalization, considering extreme cases, and mixing strategies⁷.

There are many factors to consider when looking at students' problem solving strategies. The strategy may be influenced by the type of problem^{9,10}, the ability to transfer information¹¹, the familiarity with the problem concepts¹², or the context in which the problem is being solved¹³.

Problem solvers may use a strategy based on the type of problem⁹. For example, subgoaling is the process of breaking a problem into smaller, simpler parts, which lends itself well to complex problems with multiple parts. If it is a problem similar to a problem that has already been done, considering analogous problems would be an effective problem solving strategy. This strategy requires the transfer of knowledge from one problem to another.

Problem solvers may also choose a strategy based on their level of understanding of the concepts of the problem¹². Hill climbing involves taking steps in the problem that brings one closer to the solution, which is often utilized by novice problem solvers who lack an understanding of what is required to solve the problem⁷. Hill climbing often results in dead ends, in which case the students do unnecessary work that does not help them reach the answer. Means-end analysis is similar to hill climbing except it requires a deeper understanding of the problem; it involves choosing the next step based on what will help one reach the goal. Dead-ends are less likely when using means-ends analysis, but still may occur. Forward chaining is most often used by expert problem solvers who have a deeper understanding of what is required to solve the problem⁷. When forward chaining, the problem solver plans what steps to take before starting the problem so that no unnecessary work is done⁷.

Other strategies not addressed in Nickerson's framework were considered for our analysis⁷. A strategy referred to as unit analysis, dimensional analysis, or proportional analysis commonly occurs in engineering and science. Lobato describes proportional analysis as a valuable strategy implemented by expert problem solvers¹⁴. Proportional analysis or unit analysis is the use of units to derive relationships between variables to solve the problem. This strategy is particularly useful if the student does not remember equations required to solve the problem¹⁴.

Future Time Perspectives

Student motivation is described by many different aspects including goals, beliefs, attitudes and values. This study will focus on one aspect of students' motivation: future time perspectives (FTPs). Future time perspectives are how students view long-term goals such as graduating with an engineering degree, and how these goals affect motivations and actions toward present tasks¹⁵. FTPs can be described by four factors: expectancy, perceptions of the future, perceived instrumentality, and future on present. Expectancy describes how a student expects to perform in a course⁴. Perceptions of the future describes the clarity of the students' future career goals. Perceived instrumentality describes how useful students perceive their coursework to be. And finally, future on present describes how students' present tasks influence their perceptions of the future¹⁵.

Using these four factors, students' FTPs have been conceptually represented in past research as different shapes of ice cream cones placed on axes representing instrumentality and time orientation: Sugar Cone, Waffle Cone, and Cake Cone⁶. A diagram showing the different cone types can be seen below in Figure 1: FTP Cone Types. The Sugar Cone category represents students with both a defined ideal future career and matching realistic future career. Sugar Cone students are able to connect the future to present tasks, and present tasks back to their future. Waffle Cone students had conflicting ideal future careers and realistic future careers. The Waffle Cone FTP differs from the Sugar Cone in that the Waffle Cone FTP does not have expressed outcomes from these desired future careers. Cake Cones had limited expressions of the future, with no desired future career defined⁶.

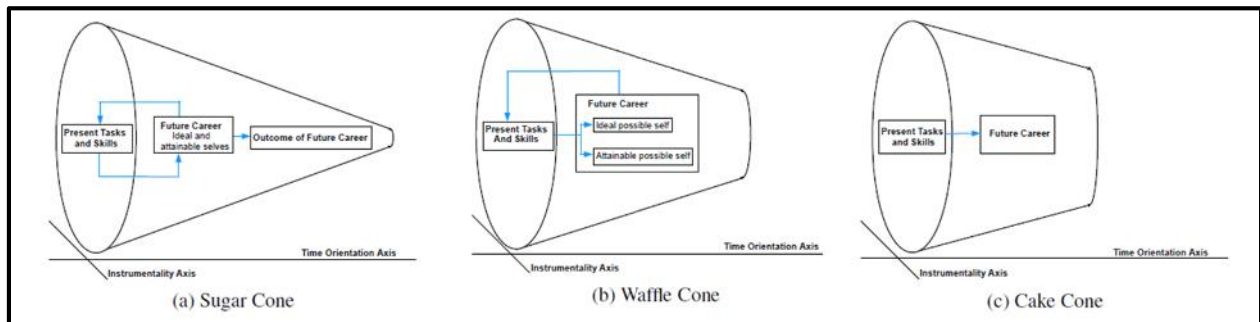


Figure 1: FTP Cone Types⁶

Past research also shows that students' perceptions of engineering problems can be driven by these FTPs. Sugar Cone students were divided into two perceptions—Sugar Cone A identifies an engineering problem as a problem with specific steps, and Sugar Cone B students describe engineering problems as having a purpose (namely, something that improves technology)⁶. The Waffle Cone students identified engineering problems as anything that makes things work; for Cake Cone students, engineering problems can be anything⁶.

Methods

Seven second and third year mechanical engineering and bioengineering students completed an open-ended engineering problem which applied statics concepts in a cell biomechanics context. The participants volunteer research participants from sophomore bioengineering and mechanical engineering courses. The problem solving sessions occurred outside of class, but applied concepts which they had seen in a statics or physics course.

The problem consisted of two sections; the first section had three questions (a, b, and c) which explored the effects different properties of the cell had on the forces exerted on the cell. The second section asked the student to discuss and justify their results from the first section. Students were encouraged to focus on the problem solving process, not the answer. Participants solved the problem with a Livescribe pen and a calculator, and had no additional resources.

Interviewers checked in periodically to monitor participant progress, but no questions were asked about the problem. Students took 25-45 minutes to solve the problem.

The problem solving interview took place immediately after the student finished the problem, and lasted about 30 minutes. The semi-structured interview began with general questions about the problem, and then prompted students to walk through their problem solution, using each student's own work for stimulated recall. Clarifying questions were asked about their strategies for solving the problem and strategies they typically implement when solving engineering problems. Student solutions and interviews were recorded using a Livescribe pen.

The problem solving interviews were analyzed for strategies using directed content analysis based on Nickerson's framework⁸. Students were asked to describe their approach to the problem, and from their descriptions, strategies were identified. Students' written work was used to triangulate the interview data. The codes and emergent codes can be seen in Table 1: Strategy Codes for Students' Interviews (I) and Written Work (W).

Theories about problem solving strategies exist, but since they have not been used in this context, directed content analysis was used, allowing for emergent codes¹⁶. Directed content analysis is used when there are existing frameworks on the topic, but may not complete, as was the case in this study. In directed content analysis, researchers begin coding using existing categories from literature; data that does not fit into these categories is analyzed for potentially new categories.

The written work was played back from the Livescribe recording and was analyzed using a coding scheme developed specifically for identifying problem solving processes in engineering students' real time work⁸. This provided a structured approach to analyze the students' written work. From the detailed coding of students' written work, strategies were further identified using the researchers' codebook. Two students' problem solving work (Caroline and Katerina) did not record on the playback function of the Livescribe pen, therefore the order in which the student completed each part of the work had to be presumed based on the physical organization of the work.

These seven students completed a semi-structured interview focusing on the students' motivation one to two weeks prior to the problem solving interviews. A phenomenological study of the interview data was conducted to characterize students according to their FTP cone type which identified: well-defined ideal future careers, conflicting ideal and realistic future careers, and no defined future career⁶. The students' FTPs were then compared to their strategy use in order to identify any connections.

Table 1: Strategy codes for analyzing students' interviews (I) and written work (W).		
Strategy Name	Nickerson's ⁷ Description	Interpretation for Interviews (I) and Written Work (W)
Subgoalting	Breaking down a complex problem into a set of simpler problems or parts, and solving the problem through combining the solutions to the simpler sub-problems	I: Student talks about having to find different parts of the problem and use those parts to find the solution. W: Students have clearly defined solutions before the final answer that are used to find the final answer.
Hill Climbing	Progressing towards the solutions not by following a clear path, but rather only taking steps that bring you closer to the solution, if you find yourself farther from the solution, start again at an earlier point.	I: Student talks about starting the problem without a plan or a clear idea of a path. W: Student has no obvious planning by writing out the knowns and unknowns. Student has work crossed out, potentially in multiple places, or has unnecessary work
Means-End Analysis	Similar to hill climbing, but is more flexible. The student identifies the goal state and the current state, and taking the path that brings you closer to the goal.	I: Student talks about planning and understanding the goal of the problem. Student states that they have some idea of the path they will take before starting, but not a concrete plan. W: Student identifies knowns and unknowns. Student has minimal unnecessary work.
Forward Chaining	Working directly towards the goal, starting with the givens.	I: Student talks about thinking through exactly how they will reach the goal. W: Student identifies knowns and unknowns. Student may have drawn a representation of the relationships of the variables. The student's work has no unnecessary work, and no procedural errors.
Considering Analogous Problem*	Finding the solution to a similar, yet easier problem, potentially a problem the solver has already solved.	I: Student talks about using the same method as a problem from a different class. Student talks about using the same method on different parts of the problem. W: Student repeats the same procedure for multiple parts of the problem.
*Consider analogous problem can include problems from class or earlier parts of the same problem.		

Results

Students often had difficulty explicitly discussing their problem solving strategies; as a result an exact strategy could not be determined from the interviews alone. Triangulating results from the interviews with the students' written work was beneficial in understanding what students were thinking and doing while solving the problem. The results from the students' written work and interviews were analyzed together, and in most cases corroborated each other. Information from the interviews filled gaps in information within the written work and vice versa, resulting in a

final description of the strategies used by each student while solving the problem. These results are described and discussed below and summarized in Table 2: Summary of results from written and interview data.

Bonnie (Sugar Cone A: well-defined ideal future career):

Bonnie used means-end analysis and subgoaling. Bonnie's work was well organized, included diagrams to represent the relationships between the variables, and showed very little evidence of backtracking. In her interview, Bonnie discussed monitoring her progress often throughout the problem and organizing the variables at the beginning, but she did not discuss her planning stage beyond organizing the information. The organization and lack of backtracking in the written work could indicate forward chaining, but the interview showed that she did not work directly towards the goal with a concrete plan. She approached the problem with idea of how the variables may relate to the end goal and began working with the goal in mind, which is means-end analysis rather than forward chaining. Forward chaining would be an unlikely strategy for this problem since it is an unfamiliar problem.

Bonnie did not discuss the use of subgoaling in her interview; however, in her written work she solved for the angle and then used that in the rest of the problem, which is subgoaling.

Subgoaling is a good strategy for the use of monitoring, since the progress towards the goal can be assessed at the end of each simpler sub-problem.

Silas (Sugar Cone A: well-defined ideal future career):

Silas used means-end analysis, subgoaling, and unit analysis. Neither Silas's interview nor his written work provided a clear idea of his problem solving strategies, but when analyzed together, revealed the strategies used. In his interview, Silas discussed what strategies he typically uses to solve an unfamiliar problem, but did not reflect on this specific problem. His work showed some evidence of planning; however, there is also some backtracking.

During his interview, when he is asked what he does when he has to solve a problem he is not familiar with, Silas responded, "[I] try to work through the process in my head to solve the problem and then see if something works." This description matches the definition of forward chaining very closely. Silas considered the use of higher level strategies, but since there was backtracking in his written work he did not plan out the direct path to the goal and stick with it. From this additional information in the written work, it can be determined that means-end analysis was used. Although he did not discuss unit analysis or subgoaling in his interview, his written work shows the use of both.

Katerina (Sugar Cone B: well-defined ideal future career):

Katerina used a combination of means-end analysis, "considering analogous problem," and unit analysis. Her written work showed some organization and planning, and there was no backtracking—she worked directly towards the goal. She focused on the importance of

proportions in her reflection. She described comparing information from different parts of the problem to create what she describes as “proportions.”

Katerina described hill climbing when asked what she normally does with an unfamiliar problem. Hill climbing may not be an uncommon strategy for students with little experience approaching an unfamiliar problem. However, her written work for this problem indicated a more organized, well-planned approach. When considering both the written work and audio reflection, the apparent strategy indicated is means-end analysis. She used the same procedures in part a, b, and c indicating the use of analogous problem. Her discussion of proportions in the audio reflections indicated the use of unit analysis, which fit with her written work, but would be unclear from her written work alone.

Katherine (Sugar Cone B: well-defined ideal future career):

Katherine used the strategies: hill climbing and “considering analogous problem.” From both her written work and interview, Katherine approached the problem in unorganized and unplanned manner.

In her interview, Katherine described trying to solve the problem using a method she learned in class, but when there wasn’t enough information to do it that way, she switched to a more brute force method: “I knew that I had to like start the problem and then I’d kind of figure out what I was doing all the way.” Katherine started using “considering analogous problems” from class, but turned to hill climbing. In her work she bounced between parts of the problem before completing any one part. She uses the same procedure in each part of the problem indicating the use of “considering analogous problems” from previous parts of the problem. She reworked the problem correctly during the interview with a little prompting after having a “eureka” moment on what she did wrong the first time. She used the same strategies (hill climbing and “using analogous problems”) when reworking the problem.

Matt (Sugar Cone B: well-defined ideal future career):

Matt used means-end analysis, “considering analogous problems,” and subgoaling. Matt described his thought process in the interview as “considering an analogous problems” from class at first, which led him to an idea of how to proceed with the problem.

There was minimal backtracking in his written work. He drew a diagram to indicate relationships between variables, indicating some planning. His primary strategy was means-end analysis. Matt described in his interview relating the problem to a similar problem in class, so he used “considering analogous problems” from class in his initial planning phase. He also used “considering analogous problems” from previous parts of the problem by using the same procedure in part b as he did in part a.

Stefan (Waffle Cone: conflicting ideal and realistic future careers):

Stefan's work was clearly driven by unit analysis. He also uses hill climbing and "considering analogous problems."

Unit analysis was discernable from Stefan's written work; he found a governing equation by comparing the units of what he has and what he needs. In his interview, Stefan described unit analysis as his strategy for most problems he is unfamiliar with, including this problem. He described the advantages of breaking down a problem into the International System of Units (SI):

"I feel like once you're in SI units that kind of gives you like a formula and you can see exactly what you need. If you need a distance you can see meters, if you need time, you can see seconds. So once you have things broken down you can kind of see how to work with them to get what you want."

He backtracked often in his work, doing and crossing out unnecessary work that led to dead-ends; this indicated hill climbing. He also used the strategy, "considering analogous problem" from previous parts of the problem, by using the same equation and procedures for parts b and c as he did in part a.

Caroline (Cake Cone: no defined future career):

Caroline used the strategies: means-end analysis and "considering analogous problems." She spent a large portion of the time conceptualizing the problem by relating variables and posing questions about the problem statement.

In her interview, Caroline spent time trying to understand the information, but never decided on a detailed path to take. Her written work also indicated planning throughout, such as identifying unknowns, equations she may need, and drawing a diagram, but there is some backtracking when she used the wrong equation. When asked what she normally does after writing down all of the initial information, Caroline simply responded "[I] try to solve it." So she normally spends time understanding the question, but does not completely plan through her procedure, which indicates both in her normal approach and her approach in this problem that she utilized means-end analysis. Caroline also used "considering analogous problems" on part b by following the same procedure as in part a.

Discussion

Students' problem solving strategies were compared to how students perceive the future and how these students perceived engineering problems, and no connections were found. Although there was no apparent connection between the students' problem solving strategies and their FTPs, some patterns in strategy use could be discerned across students. The only strategies that were used by the students in this study were means-end analysis, hill climbing, subgoaling, considering analogous problems, and unit analysis. From the students' work it seemed that hill

climbing, means-end analysis, and forward chaining are all descriptions of the general approach of the entire problem, while subgoaling, unit analysis, and considering analogous problem are all more specific ways in which these general approaches are executed.

The problem seems to have been more conducive to certain approaches such as subgoaling and considering analogous problem. The type of problem and the setting in which the problem was solved has been shown to influence students' problem solving strategies⁹. The problem was not worked in an authentic classroom setting; the problem was not directly connected to concepts that were being discussed in a class; and students had never seen this problem or type of problem before. These aspects could explain the strategies that were used and the strategies were not used, as was described in the theoretical framework section.

Table 2: Summary of results from written and interview data, both combined and individually

Name	FTP Cone	Combined	Written	Interview
Bonnie	Sugar Cone A	Means-End Subgoaling	Means-End Subgoaling	Means-end
Silas	Sugar Cone A	Means-End Subgoaling Unit Analysis	Means-End or Hill Climbing Subgoaling Unit Analysis	Forward chaining (usually)
Katerina	Sugar Cone B	Means-End Unit Analysis Analogous Problem-p	Unit Analysis Forward Chaining	Unit Analysis Hill climbing or Means-end
Katherine	Sugar Cone B	Hill Climbing Analogous Problem -p Analogous Problem -c	Analogous Problem -p Hill Climbing	Analogous problem -c Hill Climbing
Matt	Sugar Cone B	Means-End Analogous Problem -p Analogous Problem -c Subgoaling	Analogous Problem - p Means-End Subgoaling	Analogous Problem -c Hill climbing or means-end
Stefan	Waffle Cone	Hill Climbing Unit Analysis Analogous Problem -p	Unit Analysis Hill Climbing Analogous Problem -p	Unit analysis
Caroline	Cake Cone	Means-End Analogous Problem -p	Means-End Analogous Problem -p	Means-end
Analogous Problem – c refers to considering an analogous problem from class Analogous Problem - p refers to considering an analogous portion of the same problem.				

Forward chaining is a strategy used by experts familiar with the type of problem⁷; since this was an unfamiliar problem for the student, it was not surprising that forward chaining was not used by any student. Subgoaling is conducive for the frequent monitoring of the progress towards the goal, which is required in means-end analysis. Unit analysis is a strategy that is useful when there is no other information about how to approach the problem. As Stefan demonstrates, unit analysis can be used to discover a governing equation, also useful in an unfamiliar problem.

“Considering analogous problems,” using a previous part of the problem, was a beneficial strategy for this problem since similar methods could be used for each part. “Considering analogous problems,” a problem from class, is a strategy that is often intentionally or unintentionally encouraged by homework and example problems. Students will follow the procedures from an example problem in order to solve an assignment problem¹⁷. This may be why two students’ first response for the problem was to try to use an example in class. In both cases, the attempts were not successful, most likely because these problems were worked outside of the classroom setting and not connected directly to concepts being covered in class at that time. An inauthentic environment may not facilitate student transfer¹¹.

Conclusions and Implications

This paper sought to find connections between second year engineering students problem solving strategies and their FTPs in order to personalize students’ learning experience and improve their problem solving processes by appealing to their motivations. Students’ problem solving strategies were characterized using Nickerson’s framework, and an additional strategy, unit analysis was identified⁹. By combining students’ written problem solving work and the students’ audio descriptions of their problem solving work, student problem solving strategies could be characterized with a primary strategy of either means-end analysis or hill climbing along with secondary strategies of subgoaling, unit analysis, and utilizing an analogous problem.

Although students’ problem solving strategies showed no connections to their FTPs, the methodology in this study will aid future studies that require identifying problem solving strategies. Results from combining written work and audio recordings of post-hoc reflections provides a better understanding of student’s problem solving processes than either data source on its own, and this approach of combining data sources will be used in our future studies.

Future Work

Future research on connections between problem solving and motivation may need to focus on other aspects of problem solving, such as knowledge transfer or conceptual understanding, rather than problem solving strategies. Also, the use of different problem types in engineering environments could be explored in order to understand how these influence student problem solving strategies and their motivations.

One limitation was the low number of participants (n=7); this study may not have reached saturation. Future research will include a conceptual replication study of the identification of students’ FTPs, and how their perceptions of the future connect to aspects of problem solving⁶.

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