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WIP: Scaffolding the Metacognitive Problem-Solving Process in an Undergraduate Engineering Peer-Review Project

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Abstract

This work-in-progress (WIP) research paper presents a student engineering project that employs the PROCESS framework (**P**roblem definition, **R**epresenting the problem, **O**rganizing information, **C**alculations, **E**valuating the solution, **S**olution communication, and **S**elf-assessment) to enhance metacognitive problem-solving strategies. The project includes a series of workshops, think-aloud recordings, and peer reviews aimed at first-semester students in a non-traditional, co-op-based engineering program. The primary goal of the project and its associated research is to improve students' metacognitive skills and problem-solving abilities. Future research will focus on formal data collection and analysis to validate these preliminary findings and explore the framework's broader applicability.

Introduction

The purpose of this *work in progress* paper is to present a multi-week problem-solving project and the associated research methodology for improvement of student learning outcomes. Problem-solving is considered an essential skill for graduating engineering students [1], [2], as this new generation of engineers will need to solve multi-faceted, complex social, technical, and ethical issues using interdisciplinary, collaborative, data-driven, and systematic approaches [3], [4].

Background and Theoretical Frameworks

To solve these complex, ill-defined social problems, students must first learn the processes and develop frameworks for concepts and procedures behind solving well-defined technical problems [5]. One crucial component of problem-solving is metacognition, the process of reflecting on one's own learning processes including planning, monitoring, and evaluating that learning [6], [7], [8]. Metacognition, commonly referred to as "thinking about thinking," is essential for self-directed learning (SDL) [9], [10] involves being aware of what one knows and does not know and then regulating that knowledge. Novice problem-solvers often use inefficient or incorrect methods, leading to performance errors and a lack of self-assessment [8], [11], [12]. First year engineering students typically have limited exposure to and struggle with the foundational skills and necessary processes to solve engineering problems [13]. Metacognitive processes during problem-solving, such as more appropriate planning and the use of structured strategies, can help students catch more errors and identify better future problem-solving strategies [14], [15]. In particular, using think-aloud during problem-solving has been shown to improve metacognitive and cognitive processes, along with supporting SDL behaviors, such as identifying resources, during the problem-solving process [16], [17].

This student project used the PROCESS framework, a seven-step process, including **P**roblem definition, **R**epresenting the problem, **O**rganizing information, **C**alculations, **E**valuating the solution, **S**olution communication, and **S**elf-assessment, to standardize assessment for problem-solving in first-year engineering courses [15], [18]. Established to make problem-solving more accessible for undergraduates, PROCESS has been validated and successfully implemented in various learning models [19] at Clemson University. This project extends PROCESS research [14], [15], [20], [21] into a multi-stage initiative, including peer reviews, to enhance metacognitive strategy use during problem-solving. The research questions, with a focus on both student learning and evaluation of the project, are as follows:

1) What do engineering students learn in relation to problem-solving and metacognitive skills through a think-aloud and peer review project in an introductory engineering course?
    a) What problem-solving strategies do students use when conducting a think-aloud in an introductory engineering class?
    b) What strategies are students learning from the peer review process of a think-aloud recording?
2) In what ways can the multi-week peer review problem-solving project be strengthened?
    a) What benefits are students perceiving from the project?
    b) What suggestions do students have regarding the project?

Methods

Participants

The Iron Range Engineering (IRE) program [22] is a five-semester, upper division engineering program. The program is stationed in Virginia, MN as a remote site of Minnesota State University, Mankato, though all activities in the program are run in a hybrid mode. This study is conducted during students' first semester with the program, which is called their Bell Academy [23]. This semester preps them for four semesters that will be spent in full-time engineering work in co-ops as well as full-time school. IRE is run as a three part curriculum: technical, design, and professionalism. Students attend required weekly one-hour self-directed learning workshops [24] as part of a one-credit professionalism course, focused on research to practice strategies that they can use both as students and professional engineers as they transition to their co-op semesters and beyond. All students in their Bell Academy are required to participate in this project.

The Peer Review Problem-Solving Project

To integrate technical problem-solving and newly learned SDL processes, students complete a multi-week project involving workshops, think-aloud recordings, and peer reviews. The student learning outcomes for the project are:

- Demonstrate mastery of problem-solving techniques in a technical context.
- Develop and enhance metacognitive awareness of their own learning and problem-solving strategies.
- Integrate problem-solving skills with metacognitive strategies to improve future problem-solving performance.
- Participate effectively in peer review, giving and receiving constructive feedback on problem-solving processes.
- Refine problem-solving strategies through analysis of a peer’s think-aloud.

Students learn about metacognition in a workshop and complete an assessment related to their design work, including reflective activities to understand how their metacognitive strategies impact their work. Students then complete a pre-assignment about problem types and structures [25], [26] and attend a problem-solving workshop, where they learn about metacognitive strategies in engineering, the PROCESS framework, and think-aloud as a problem-solving tool. The students are taught to use the PROCESS Problem-Solving Template in Figure 1 as a foundation for their problem structures. Students conduct an individual, recorded think-aloud session (Appendix A) using the PROCESS framework and its associated template with a first-year course-based technical problem.

Present the problem	Represent by modeling	Organize other information
Convert the inputs	Calculate unknown values	Convert the outputs
Express the answer	Support your thinking	

Figure 1: Peer Review Project PROCESS Problem-Solving Template showing Plan (top row), Analyze (middle row), and Reflect (bottom row) sections, adapted from [21] and [20]

After submitting their think-aloud, graded for credit, students are randomly assigned to review one another's processes using the PROCESS template and grading rubric (Figure 2), providing feedback and learning about their peer's metacognitive strategies. See Appendix B for sample peer review assignment instructions.

Problem Solving PROCESS	Accuracy	Learning Outcome GAINs			
(7 iterative stages)	Errors occurring within the stage	Great	Adequate	Insufficient	Not demonstrated
Present the Problem □ Identify desired variables & units □ Identify problem constraint(s) □ Communicate assumption(s)	□ Misinterpreted what to solve for (unknown) □ Ignored constraints □ Misinterpreted constraint(s) □ Invalid assumption(s)	3	2	1	0
Represent by modeling □ Sketch a representation of relationships □ Identify relevant theoretical equations □ Match given values to variables	□ Incorrect variables represented □ Used wrong theory as a model □ Incorrect relationship between variables	3	2	1	0
Organize Information □ Identify known values □ Identify reasonable limits on variables □ Identify conversion factors	□ Incorrect variable assignment □ Invalid constant/conversion factor	3	2	1	0
Calculations □ Solve for unknown variable algebraically □ Document intermediate math steps □ Convert to SI units □ Input values into equation □ Convert to desired units	□ Inconsistent units (failed to convert inputs) □ Incorrect unit derivation □ Incorrectly manipulated equation □ Miscalculation (work correct/value not) □ Other	3	2	1	0
Express the answer □ Confirm desired variable □ Check reasonableness precision □ Check units match desired	□ Did not answer the question □ Unreasonable precision (# of digits) □ Missing / Incorrect units on solution □ Other incorrect solution	3	2	1	0
Support your thinking □ Compare answer to expected value □ Ensure reasonableness based on limitations □ Justify reasoning	□ Physically unreasonable (impossible) □ Inadequate/flawed reasoning	3	2	1	0
Self-Assessment □ Rate your performance above	□ Responses were out of range □ Responses without showing work	2		1	0

Figure 2: Peer Review PROCESS Grading Rubric adapted from [20]

Problems in the Peer Review Problem-Solving Project

One commonly used problem, see Figure 3, in this project involves pressure gauges in Fluid Mechanics, where students determine both absolute and gauge pressures. This helps the students understand the difference between absolute and relative pressure. This problem comes about halfway through their coursework, so they are familiar with the typical problem structures. An additional example problem is provided in Appendix A.

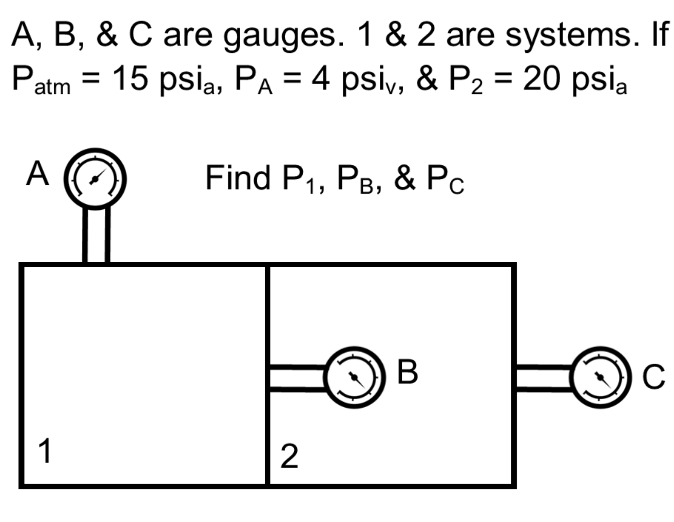

Figure 3: Example Fluid Mechanics Homework Problem for the Peer Review Problem-Solving Project

Data Sources

Data collected during the project will include recorded think-aloud sessions, written problem work, peer review rubrics, feedback, and survey data. Data will be collected from all first-semester students in the co-op-based engineering program across two semesters. Students will participate in the standard cohort experience, including technical, design, and professional coursework, and engage in all mandatory SDL workshops.

A survey, adapted from a previously used survey [18], will be provided to students at the end of the project to assess their satisfaction and learning. The survey will include a mix of quantitative and qualitative questions, with Likert scale items and open-ended items.

Data Analysis

Data analysis will use deductive-inductive or abductive coding, with *a priori* frameworks and additional emerging themes [27]. The seven-step PROCESS framework, based on task analysis [28], [29], will be the primary coding scheme for analyzing think-aloud sessions, written problem-solving, and peer review feedback. Previous problem-solving work identifying error codes [15], [30] will also be used. Qualitative survey items will be coded using the PROCESS framework and open coding, while Likert scale items will be quantitatively analyzed and compared across samples.

Quality Considerations

Validity and reliability are considered at all stages of the research process. The Q3 quality assurance framework [28] will be used to assess qualitative methods. Theoretical and procedural validity are supported by reviewing and citing research on problem-solving and metacognition, consulting experts, and updating materials based on documented research. Pragmatic and procedural validity will be ensured through careful documentation and memos. Multiple researchers will support data analysis to ensure reliability and communicative validity. Representative quotes will be identified and shared after analysis. The survey will be adapted for clarity and to assess learning outcomes based on previous literature. Finally, study takeaways will be implemented and disseminated to support future student learning and consider ethical validity.

Limitations

The study has several limitations. The non-traditional, co-op-based model with transfer and second-degree students limits the transferability of results. The program's focus on breadth over depth further impacts generalizability. Qualitative work, while rich, is limited in generalizability, and the small cohort size (40 students in fall, 20 in spring) adds to this limitation. Quantitative methodologies could increase generalizability but would reduce data richness. Potential bias exists as some authors taught the material; to mitigate this, identifiers will be removed, and experts will be consulted to maintain reflexivity.

Conclusions & Future Work

The project has been updated over several years based on informal student feedback, resulting in a smoother process and some documentation of learning outcomes. However, the project has not been officially researched for student learning or satisfaction. The described methodology provides a framework for assessing and improving the project. Future work includes refining data collection methods, addressing limitations such as varying problems across cohorts, and further assessing research quality. Future efforts will focus on identifying student learning outcomes, refining the project, and exploring new ways to introduce PROCESS and metacognitive problem-solving to a growing cohort of engineering students.

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Appendix A: The Think Aloud Assignment

Problem-Solving Post-Assignment Video Recording

Instructions

Metacognitive reflection and recording a "think aloud" while solving a problem has been shown to improve the problem-solving process and reduce errors [28].

For this assignment, please record yourself working through the assignment and doing metacognitive reflections. Record on your ipad with audio so that your audio reflections are matched with your work on the problem. You can record directly on your ipad using a screen recording (but make sure the audio is on) or record on Zoom. Make sure that as you work, you vocalize everything you're doing, including accessing the homework solution video, textbook, Googled equations, etc.
Turn in both your recording and your written solution in the Google Drive folder with your name by [date].

Tips for reflecting on your work:
Explain what you are thinking, feeling, recalling, remembering, or doing as you are working the problem. Your reflection might begin with:
" I am thinking...", " I remember...", " I recall...", "I wonder..."

Explain why you are doing what you are doing (not just what you are doing, and your motivation or expectations for writing something down. Your reflection might begin with:
"I want to...", "In an earlier problem I______, so here I ...", "I know that by...", "I expect..."

If you encountered anything surprising in your work (or even while replaying your work), tell us about it. Such a reflection might start with:
"I am surprised to find that…" or "I didn't realize until now that…"

For Fluids: See assignment from Fluids (4.2 Gauges). Contact your professor with any questions.

For anyone not enrolled in Fluids: Select a partner (or group) who is in your [first semester] cohort and work together to select a problem from a current class to record. Notify your professor once you've selected by [date] for approval. When picking a problem, consider one that will be useful to do a deep dive and learn extremely well but also is reasonable to record. If you do not select a problem by [date], you will need to complete the following Engineering Economics problem:

Suppose that we are analyzing the following six alternatives for a small investment project using the IRR method. The useful life for each alternative is 10 years and MARR is 10% per year.

	A	B	C	D	E	F
Capital investment	900	1500	2500	4000	5000	7000
Annual Revenue-Expenses	150	276	400	925	1125	1425

a. If the alternatives are independent, which one(s) are acceptable?
b. If the alternatives are mutually exclusive, which one(s) are acceptable?

Appendix B: The Peer-Review Assignment

Instructions

Please read through the instructions below before starting. You will watch one problem-solving video and provide feedback using a designated rubric. Professionalism counts. Make sure to proofread your work and cite appropriately.

1) If you are registered for Fluids this semester, complete this assignment. If you are not taking Fluids this semester, see your professor for an alternative assignment.
2) Upload your recorded Problem-Solving Session and image/writing of your solved problem from Fluids (or alternative course assigned by your professor) into the Problem-Solving Peer Review Assignment folder.
3) Watch your assigned partner's video. Contact your professor with any questions or if your name does not appear. These will be assigned on [date] and updated as videos are uploaded.
4) Give detailed feedback using the Rubric and Template documents provided.
    a) First, find the Peer Review Problem-Solving Template and Peer Review PROCESS Grading Rubric in the Google Drive folder.
    b) Second, break your peer's problem down into steps written onto the Peer Review Problem-Solving Template. Write all of the actual (numeric, etc.) steps your peer performed into each appropriate box.
    c) Third, grade the problem with the Peer Review PROCESS Grading Rubric.
    d) Finally, provide additional detailed feedback either as a video or typed document. One way is writing feedback on each step using the Peer Review Problem-Solving Template.
5) Name all of your files in this format: YourFirst&LastName_First&LastNameofPartner_Item_Semester
6) Upload all completed files/items for feedback to two locations: (1) into your partner's folder for your partner to review and (2) onto Google Classroom.