Board 63: How Problem Solving Skills Develop: Studying Metacognition in a PBL Engineering Curriculum

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Introduction

Metacognition is "knowledge of one's knowledge, processes, and cognitive and affective states; and the ability to consciously and deliberately monitor and regulate one's knowledge, processes, and cognitive and affective states" [1, pp. 3]. Metacognition is a higher-order thinking skill and is critical for the development of self-directed learning. Self-directed learning, which consists of such skills as identifying one's knowledge strengths and weaknesses, questioning one's thoughts, actively searching for knowledge, and making inferences, has been identified by the Accreditation Board for Engineering and Technology (ABET) as necessary for life-long learning and an effective work career skill [2]. Although metacognition is key for students' self-directed learning, explicit instruction in metacognitive skills has been rarely integrated into engineering programs. One notable exception has been the Iron Range Engineering program (IRE). IRE is an innovative engineering program located in Virginia, Minnesota where students explicitly engage in activities to become familiar with, develop, and apply metacognitive skills within a real-world problem-based learning (PBL) environment.

The goal of our IUSE NSF project has been to study the metacognitive skills development of both students and graduates of IRE. Our research has followed a two-pronged approach: (1) identifying and understanding the metacognitive skills students develop and use during their preparation as engineers in a PBL program, and (2) examining whether the preparation of students in the PBL program (particularly in the area of metacognition) gives them a "leg up" in their *transition* to the engineering workforce. At this point of our project, we have collected and analyzed three data sources: interview data from IRE students that was collected at the beginning and end of their program, think-aloud protocol data as students solved open-ended engineering problems that was collected from the same students and at the same time stamps, and interview data from IRE alumni. Our intention in this paper is to provide an overview of results of our analyses of these data to demonstrate how explicit instruction and practice applying metacognitive skills may positively impact students' problem solving and facilitate the transition of graduating engineers to the workplace.

Iron Range Engineering

The Iron Range Engineering program offers an upper-division (junior and senior) undergraduate engineering degree (through Minnesota State University – Mankato) where students engage in a curriculum that is driven by problem-based learning. Students work in groups each semester with local industry partners who present real world projects that provide students with the opportunity to solve ill-structured problems. In collaboration with IRE faculty, students generate syllabi that describe how they will address the projects and present how the ill-structured problems meet with the IRE design and technical curriculum competencies. Throughout the semester-long projects, students work collaboratively with their groups and individually to generate a range of potential solutions to their ill-structured problems. Students self-direct their learning by seeking out a range of resources that can range from traditional printed material and digital libraries to interactions with subject matter experts such as practicing engineers and instructors.

A unique and critical feature of the IRE curriculum is its developmental focus on self-directed learning towards problem-solving. Throughout the problem-solving process, IRE students are engaged with purposefully designed metacognitive reflection activities. The reflection activities include writing memos centered on their learning and problem-solving strategies utilized while the projects are ongoing to completion, and when completed, they write on the processes that have gone into the projects, including what went well or what could have gone better. These written memos serve as metacognitive tools [3] that help students to monitor and control their thinking in the process of attaining desired outcomes—both critical components of metacognitive procedural knowledge—and to take stock of what they have learned to help transfer their newly gained knowledge to other contexts, a critical component of metacognitive declarative knowledge [1], [4]. According to theories of self-directed or self-regulated learning [5], [6], both declarative and procedural components of metacognition are necessary components for students to become “self-regulatory organisms who are capable of assessing themselves and others and directing their behavior toward specified goals” [1, pp.10].

Methods

Participants

Study participants were selected from two active cohorts of IRE students. Between the two active student cohorts, a total of twenty students participated in the entry semi-structured interview [7]. Two years later, sixteen of the original twenty participated in the exit interview with four leaving the program for a variety of reasons. For the think-alouds, seven students were randomly selected from each of the cohorts, the first starting in January 2016 and the second starting in August 2016. Two students from the first cohort left the program, which left us with 12 students who participated in the pre and post think-aloud protocols.

Data collection: Interview data from IRE active cohorts

Semi-structured interviews recorded face-to-face and transcribed for later analysis were conducted at the start of students’ program (beginning of junior year) and again near the completion of their program (end of senior year). The interviews lasted between 20 and 45 minutes. The interviews explored and compared the following topics:

- Background information such as prior college experience and preparation as well as why they selected the IRE program.
- Their self-directed learning strategies.
- Which self-directed learning strategies they find useful.
- Viewpoints of what self-directed learning and metacognition are.
- Value Viewpoints of self-directed learning and metacognition.

Additionally, the second interview asked for student reflections about potential changes in their self-directed learning strategies and practices of metacognitive skills after their IRE learning experience.

Data collection: Think-aloud protocols from IRE active cohorts

The purpose of the think-aloud protocols was to capture students' conscious thinking as they solved open-ended, ill-structured, engineering design problems. The first problem involved the redesign of a dirt bike motorcycle for use as a taxi on a tropical and mountainous island. This problem was adapted from Dixon [8]. The second problem involved the redesign of a propane-fueled camp stove for use by the military in a desert combat zone. The two problems were judged by a senior engineering faculty and a professional engineer to be of equal difficulty and involving comparable redesign issues. There were eight components in each problem that students had to address. The think-alouds were recorded face-to-face and transcribed for later analysis, and like the interviews, were conducted at the start of students' program (beginning of junior year) and again near the completion of their program (end of senior year). The think-alouds lasted between 15 and 30 minutes.

Data analysis

Interview data. The student and alumni interviews were transcribed into PDF documents and uploaded into DeDoose (www.Dedoose.com), a computer-assisted qualitative data analysis software with mixed methods capability. All student and alumni interviews were analyzed conducting a Thematic Analysis [9] using research and interview question constructs as guidance towards category, code, and theme generation. Selected interviews were recursively analyzed to develop thematic codes for later application to the remainder of the interviews after establishing inter-rater reliability. Through this recursive process, codes inductively emerged and a reference coding book was developed to establish each code, its definition and examples. Two coding books were created, one for students and one for alumni. Establishing inter-rater reliability for coding consistency between researchers, DeDoose's testing feature was utilized through three coding exercises. After each exercise, instances of coding inconsistency were resolved through discussion of each instance, a process leading to improved reliability and confidence in consistency of code application. Once the coding scheme and inter-rater reliability were established, all interviews were coded for analysis. Both student and alumni categories are presented in Appendix A.

Think-aloud data. Each think-aloud protocol was divided into single utterances consisting of a subject, verb, subordinate clauses, and prepositional phrases (see Hunt, 1965 [10] for description of T-units). We then created a categorization scheme to code the utterances using a theoretical conceptualization of metacognition that we had designed earlier in the project. Our definition of metacognition identifies both declarative and procedural components of metacognition. Metacognitive declarative knowledge was divided into the subcategories of cognitive states, affective states, and knowledge of strategies. Metacognitive procedural knowledge was divided into the subcategories of monitoring and control, and monitoring was further divided into sub-subcategories of identify task, check on current progress, and evaluate. Control was also divided into subcategories; however, these subcategories were used infrequently so that we collapsed them in a single subcategory of control. We added to these a category for utterances that reflected the student's reading of the problem, a category for utterances that were judged not to be metacognitive in nature but reflected a student's knowledge of the domain in which the problem was contextualized, and a category that reflected his or her solutions to the various elements of the problem. These categories served as the basis for our categorization scheme. All categories were operationalized, and these operationalizations were further refined iteratively during the analyses of the verbal data from the first four students. The iterative process followed constant comparison methods in which changes to categories were made and agreed upon through discussion between the coders as new data were reviewed [11]. The final operationalizations are provided in Appendix B. Two people independently categorized each utterance of the verbal protocols for each student's pre- and post-problems, and agreement on the two categorizations was computed using Cohen's Kappa. Agreement between the two ranged from .64 to .91, with a mean of .81 (*SD* = .06). All disagreements were resolved through discussion.

Results

Aggregate analysis: Interview data from entering first year IRE students and metacognitive indicators

Entry interview analysis provided consistent metacognitive declarative and procedural indicators throughout with self-directed learning being a significant driving component of them. While some students stated being conceptually aware of self-directed learning (SDL) prior to their IRE experience, most expressed being introduced to the concept early in the IRE program. Students regularly conveyed trying to understand, learn and apply the SDL approaches they were being taught in the program. A continual entry interview theme was how SDL was such a departure from traditional learning. Below is an excerpt (starting with the participant ID number) expressing this theme:

#1939 "So far, it's a bit of culture shock and almost doesn't feel right. But I think that will change very soon and eventually it will feel right and I will like it better than a traditional school and I will excel in this style of learning. When I said it doesn't feel right, I mean it makes me a little nervous. I'm not used to this style of learning yet."

Throughout this data set, while focused on their course-related industry work, consistent declarative indicators include scoping project and task requirements along with using specific strategies to accomplish those tasks. Consistently displayed procedural indicators include tasks identification and their progress as well as directing resources to accomplish those tasks.

As an example, time management and planning are consistently referred to for scoping and determining strategies to successfully address tasks and projects for industry related work. The declarative presents itself as the ability to estimate how long a task will take to complete and what strategies need to be utilized in order to complete the task by the estimated time period. The procedural can present itself framed through a to-do list where monitoring occurs to identify tasks, evaluate their progress and predict their completion time. As a response to monitoring, control can determine, allocate and direct cognitive resources and steps while also helping to set the intensity and speed to help meet established goals. Related to time management and planning, this excerpt example provides metacognitive declarative and procedural instances:

#1526 "I keep a planner. The second I hear about homework or something due, I write it down immediately. I'm consistently looking through that planner throughout the whole day and am constantly updating it. I keep sticky notes on my computer. I have a sticky note with a To-Do list which I'm constantly revising and trying to keep up with it while meeting deadlines."

Data collection summary: 2 rounds with entering/graduating students

Many students emerge from traditional education and upon entering the IRE program are formally introduced to metacognition (declarative and procedural), "learning how to learn" (the journey of discovering their own learning style) and self-directed learning concepts to utilize throughout their student journey and into their professional careers. As previously mentioned, students emerging from traditional learning backgrounds must adapt to a more unfamiliar self-directed learning environment which was challenging for some. While initially adapting to self-directed learning, this excerpt presents early use of metacognitive elements (noted within the excerpt) being considered to help meet the challenge:

#1316.1 "I'm definitely struggling with exactly how I need to set it (SDL) up. What I have grasped is that we have a syllabus with goals and expectations and things like that (declarative). *Because I know the goals I need to meet* (procedural monitoring), *I set periods out of my week where I'll study a certain topic at a certain time* (procedural control)*."*

In the exit interviews, students have a much more tangible grasp of what metacognition and self-directed learning mean to them along with a perceived sense of an enhanced ability to use them. Being familiar enough with how to apply them that they feel almost second nature. The below themes express these concepts:

#1188 "I came in with some self-directed learning but IRE definitely added to those SDL skills. 2 years ago, I wouldn't have been able to get through an electronics class without the improved SDL techniques I learned here."

#1210 "But after experience with SDL, it's becoming more natural and more of an easy flow for me to get into. I think it's more convenient learning on your own because you direct yourself and find the things you need to learn."

We also revisited participant #1316 (from previous quote #1316.1) to see how their independent learning struggles were addressed after being in the program for two years:

#1316.2 "I'm just trying to kind of take a somewhat metacognitive approach now. Figuring out what I know and what I don't know. It's recognizing when I need to go more in-depth into certain learning aspects and branching off kind of in that aspect. From there I can kind of base on like what I need to learn to accomplish my goals."

Interview sessions revealed students initially believed SDL strategies would be critical to their success at IRE as student's along with a later (exit interview) recognition of their future relevance in the workplace:

#1188 "Now that I'm close to being finished with school, SDL is going to take on a new meaning. I'll be working as a reliability engineer at a fairly good-sized company. There will be things I need to figure out and there might not be anybody to ask there that I have to ask questions. I will have to find resources, do the engineering work and learn things on my own. That will be self-directed."

Also consistently mentioned in both (first and second) interviews is IRE's stressed "learning how to learn" concept to support self-directed learning towards problem solving. Once presented at the start of their IRE program, students begin to better understand their own learning approaches of what works best for them and its connected support resources and techniques. While less defined initially, by the end of their program, multiple IRE students had a strong sense of what learning approaches and techniques work best for them:

#1711 "I came up with these techniques based on a mixture of both my needs and IRE. A big thing IRE does is introduce you to a number of techniques you might like but 90% of them sound tedious and unnecessary to me but other students might like those techniques and use them to be successful. It's sort of like the Spaghetti method, throw the techniques at the wall and see what sticks for people. All of those things about asking the right questions, I learned at IRE. There's nothing I'm doing that IRE didn't mention."

Through this understanding, they can more consciously and flexibly regulate their resource and technique selection depending on the problem and context. Some learning resources and techniques presented themselves in the first interviews (e.g., online information gathering, utilizing subject matter experts, etc.) with the second interviews showing a greater range of number and type (e.g., Google Drive, mind maps, Gantt charts, SCRUM charts, interleaved space retrieval, etc.), some (not listed here) unique to the IRE program.

Analysis of think-aloud protocols

The think aloud data were analyzed through verbal utterances having metacognitive related categories and subcategories based on how the data presented itself. Metacognitive monitoring included subcategories of identify tasks, check on progress and evaluate progress. Metacognitive declarative knowledge included subcategories of cognitive states, affective states and knowledge of strategy. Stand-alone categories included metacognitive control, domain knowledge, solution, and reads problem. The subcategories under the heading Metacognitive Control were collapsed into one category because either the subcategories were not used or there were too few utterances categorized under each. Although there were too few students to conduct valid inferential statistical tests, given the exploratory nature of the current study, we did conduct a repeated measure analysis of variance (RMANOVA) to identify potential trends in the data. Each category served as a repeated measure, and the dependent variables were the pretest and posttest percentages of each type of verbal utterance for each student. There was not a significant difference between overall pretest means and posttest means, Wilks' Lambda, $F(10, 2) = 2.98$, $p = .28$, indicating that across combined categories there was little change in students' verbal utterances from pretest to posttest. However, univariate tests using the Greenhouse-Geiser correction showed significant differences for Identify Task ($p = .028$, $\eta^2_p = .37$), Knowledge of Strategies ($p = .006$, $\eta^2_p = .51$), Domain Knowledge ($p = .018$, $\eta^2_p = .41$), and Reads Problem ($p = .005$, $\eta^2_p = .52$).

These results suggest that students had a shift in attention from pretest to posttest in these four areas. Students did read both problems in their entirety and did identify most if not all of the components in the two problems; however, in their overall problem solving they diverted a portion of their attention from identifying the components of the problem (5.18 vs. 3.42) and reading the problem (21.78 vs. 13.43) to using strategies (.90 vs. 5.78) and using their domain knowledge to solve the problems (19.07 vs. 25.72). Because the pretest and posttest problems were approximately the same length in words and consisted of the same number of components, the decreases in these two categories cannot be attributed to fewer words to read or fewer components to identify. A tentative explanation for the increased attention given to strategies and domain knowledge is that students were using strategies and domain knowledge that they had learned during the course of their studies at IRE. This was particularly evident in the use of strategies because the strategies identified in their verbal protocols could be directly linked to strategies they had learned at IRE. An important follow-up question we intend to pursue is whether the increased attention given to strategies and the use of domain knowledge resulted in higher quality answers.

Discussion

Many students who enter the IRE program have minimal defined understanding of what metacognition is and its benefits, what self-directed learning means and how to perform it nor a formed understanding of different learning styles and what works best for them. Once these concepts are introduced to them, there is an understanding of their potential benefit as both students navigating the IRE program and later in their professional careers as they approach and solve ill-structured problems. With most students coming from traditionally structured education backgrounds, adapting to a program that not only teaches these concepts but functions by them can be challenging. To meet these challenges, students learn and practice a number of self-directed strategies and well as discover their own learning style by “learning how to learn” which is rooted in metacognitive aspects of the declarative and procedural. Through this learning and practicing process, students become empowered to successfully progress though their coursework and grow their real-world problem-solving skills while immersed within IRE sponsored industry projects. By the end of their IRE programs, students have not only embraced metacognitive concepts, “learning how to learn” and SDL techniques but have become so comfortable and familiar through their utilization, that they have become second nature towards problem solving. As practicing engineers, former IRE students consistently pointed to their co-op industry projects as pivotal training grounds to apply and adjust the concepts and techniques learned at IRE toward improving their performance, approaches they still utilized. With metacognition, the declarative was regularly presented when discussing project scoping and which problem-solving strategies to utilize. Monitoring and control were regularly presented by establishing tasks, checking on their progress and by regulating any resources or needed adjustments to accomplish established goals. Also having a significant impact on their workplace performance is having a firm grasp on which approach to learning works best for them. When presented with a problem, they are equipped to quickly identify which style of learning and technique(s) best apply to the situation enabling them to address problems in a timelier manner. While metacognition and SDL skills sets can be applied to familiar problems, they also provide value in approaching unfamiliar problems. IRE alumni consistently reported earning confidence from peers and supervisors through a versatile ability of routinely solving unfamiliar problems making the alumni valuable workplace assets.

Future Directions and Significance

We have identified three areas of research we intend to pursue. First, we will continue to triangulate the think-aloud data with students' self-report interview data but on an individual basis. Examining the relations between what a student believes to be how he or she self-directs his or her learning with how learning is actually self-directed during problem solving will uncover concordances or discordances between beliefs and behaviors. Bringing the two closer together could potentially increase the effectiveness of self-directed learning in engineering education. Second, we intend to examine the quality of each student's problem solving by asking a professional engineer to evaluate solution-related statements from the transcripts of each student. Discovering the associations between various aspects of metacognition and quality of thinking could not only confirm the important connections between metacognition and problem solving but provide direction in what aspects of metacognition need to be emphasized in an engineering curriculum to promote self-directed learning. And third, in our current research, we have examined only the degree to which various aspects of metacognition are present during problem solving. What might be more important is to examine when various aspects of metacognition occur. For example, when is the optimal time for monitoring to occur, or when should control be exerted to direct or redirect attention to key components of a problem? Therefore, we will track the kinds and sequences of metacognitive and non-metacognitive thoughts made by students as they proceed through the problem-solving process. By identifying the sequences of thoughts that lead to quality solutions, we will be able to address an essential question about the role of metacognition: How does the use of metacognitive processes inherent in self-directed learning during problem solving contribute to higher quality engineering problem solving.

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Appendix A

Student and Alumni Categories Used in Interview Analyses

Student Categories **w/ code examples**	**Alumni Categories** **w/code examples**
Learner Characteristics ● Gender ● Prior Engineering Experience	**Work History** ● Promotion History ● Current Work
IRE Learning Environments ● Resource Accessibility ● Teacher Accessibility	**School to Work Transition** ● School vs Work Difference ● Task Approach Strategy
Self-Directed Learning (SDL): Definition ● Procedural ● Metacognitive	**Use of Metacognition** ● Definition ● Examples
SDL: Strategies ● Goal-Setting and Planning ● Help-Seeking	**Comparison with Other Employees** ● Transition into Workplace ● Metacognition Use
SDL: Values ● IRE SDL Values ● Job SDL Values	**Comments About IRE** ● Feedback about IRE
SDL: Self-Assessment	

Appendix B

Operationalizations of the Categories of Metacognition

Metacognitive Control	Determine and Direct Steps:	The statement identifies future steps or procedures that will be taken to solve a specific component of the problem and sometimes indicates when the steps or procedures will be taken. The statement explicitly or implicitly indicates that the problem solver is in executive control or oversight of the problem-solving process. The verb is generally future tense or can take the imperative form. The statement contains "I" or "we."
	Allocate Resources	The statement indicates that attentional or cognitive resources are being directed to a specific aspect of the problem or that there is a shift in attention or cognitive resources from one component of the problem to another.
	Set Intensity of Work	The statement indicates that effort is being directed to a specific component of the problem, or effort is being diverted from a specific component, or effort is being maintained.
	Set Speed of Work	The statement indicates that the solution process is being slowed to allow greater focus, hastened to move onto other components of the problem, or maintained.
Metacognitive Monitoring	Identify the Task	The statement identifies a specific component of the problem that needs to be considered. Based on the statement, there is no indication that the identified component will be undertaken, only that it is something that needs to be considered. In general, these statements contain a present tense verb and do not contain an "I" or a "we."
	Check on Current Progress	The statement indicates reflection on progress made or not made on an already identified component of the problem or is considering what additional directions may need to be undertaken to arrive at a solution. Some statements also may indicate that a previously identified component (see Identify the Task) is being revisited or rechecked or that alternatives to the problem solution are being considered. In general, these statements contain a present tense verb and can be in interrogative form and may or may not contain an "I" or a "we."
	Evaluate Progress	The statement indicates an evaluative judgment is made on whether a problem-solving process or outcome is adequate, will lead to an expected outcome, needs to be modified or abandoned, or prioritizes problem solving steps in terms of their importance. The evaluative judgment is made after or during the process or the outcome has been obtained. Verb tense can be past, present, or future, and a personal pronoun may or may not be present.
	Predict Outcome	The statement indicates that an anticipated outcome of the problem solving will be forthcoming.

Metacognitive Declarative Knowledge	Cognitive States	The statement indicates a mental state, such a knowing or not knowing, currently thinking, is uncertain or confused. The statement may also indicate the problem solver is carefully weighing aspects of the problem or is engaged in reflection on it. The statement contains "I" or "we."
	Affective States	The statement indicates an affective state, such as liking or disliking something, having fun, or being bored. The statement contains "I" or "we."
	Knowledge of Task	The statement indicates how the problem can be solved, how easy or difficult the problem will be, or how the problem solution will change with changing conditions. The statement contains "I" or "we."
	Knowledge of Strategy	The statement identifies a process or procedure for solving a part or all of the problem, and the process or procedure could be transferred to different contexts. The statement contains "I" or "we."
	Domain Knowledge	The statement indicates recall or use of domain-specific knowledge, including both declarative and procedural knowledge, drawn from the domain in which the problem is contextualized. The statement may also indicate the recall of solution processes that can be associated with that domain-specific knowledge.
	Solution	The statement provides a solution to one or more of the design elements of the problem. There were eight elements to address: robust construction, costs minimized, construction to withstand a wet climate, increased cargo carrying capacity, more comfortable back seat, motor cycle rack improved, more powerful engine, theft protection of helmets.