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Improving students' metacognitive processes through predictive and reflective practices

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ABSTRACT

CONTEXT

Engineering educators face the challenge of not only preparing students with technical skills but also with the ability to adapt, problem-solve, and innovate in dynamic professional environments. Metacognitive abilities, which involve self-awareness and self-regulation of one's cognitive processes, are increasingly recognised as essential for developing these skills and leading to success in engineering practice. However, assessment practices often cause students to focus on obtaining the 'correct' answer to problems, rather than evaluating the cognitive processes involved in formulating their approach to tackle the problem, assessing the knowledge or skills that might be required, and reflecting on the execution of the process of problem solution. This lack of awareness can hinder future learning and is therefore important for educators to address.

PURPOSE OR GOAL

Metacognition plays a crucial role in learning and academic success, allowing students to become more effective learners by understanding how they learn best and by employing strategies to enhance their learning process. The purpose of this study is to implement and evaluate activities aimed at improving the metacognitive abilities of engineering students, through both predictive (pre-activity) and reflective (post-activity) tasks. Enhancing students' awareness of their own cognitive processes, their ability to monitor and regulate these processes, and their strategic approach to learning and problem-solving can lead to improved learning

APPROACH OR METHODOLOGY/METHODS

Students' metacognitive abilities were assessed via predictive (planning) and reflective (evaluating) activities associated with completing a set of problems, where they were required to self-assess items such as the perceived difficulty of the problem, which concepts might be involved, and their process to achieve a solution. Qualitative and quantitative analyses were performed to assess the effectiveness of the activities in improving students' metacognition.

ACTUAL OR ANTICIPATED OUTCOMES

Initial surveys revealed that students do not typically practice metacognition, especially when obtaining correct solutions. End-of-semester findings have shown that students perceived an improvement in both their metacognitive and problem-solving abilities through the activities.

CONCLUSIONS/RECOMMENDATIONS/SUMMARY

This paper presents activities associated with a set of problems designed to evaluate and improve students' metacognitive abilities, such as planning, monitoring, and evaluating their problem-solving approaches. Through building such abilities, students will better understand how they learn, solve problems, and make decisions, leading to becoming more effective learners.

KEYWORDS
Reflection, metacognition, problem-solving

Introduction

Engineering educators face the challenge of preparing students not only with the technical skills they might require for their chosen disciplinary specialisation, but also with the ability to adapt, problem-solve, and innovate in dynamic professional environments (Beagon & Bowe, 2023). This adaptability is crucial in a rapidly changing technological landscape, where engineers are continually engaging with ill-structured and ill-defined real-world problems and must continuously learn and innovate (Brunhaver et al., 2017).

Metacognition, often described as "thinking about thinking", serves as an important foundation in the development of engineers who are adept at problem-solving (Dunlosky & Metcalfe, 2008). In the professional setting, engineers frequently grapple with multifaceted, poorly structured, and ambiguously defined real-world challenges. The development and refinement of metacognitive abilities is therefore vital in navigating these scenarios, empowering engineers to both devise solutions with heightened efficiency and effectiveness and to continuously learn and grow from their experiences.

Metacognition involves the self-awareness and self-regulation of one's own cognitive processes, encompassing the following competencies (Bransford et al., 2000; Flavell, 1979; Palinscar & Brown, 1984):

- Identification and delineation of problems and their components
- Evaluation of how established strategies apply to specific challenges
- Strategic planning and monitoring of solution processes
- Critical assessment of both methodologies and outcomes.

These competencies not only improve engineering students' academic performance but also lay the groundwork for self-regulated learning (Zimmerman, 2002). The two key components of metacognition are *metacognitive knowledge* and *metacognitive regulation*, which refer to the awareness and management, respectively, of one's own cognitive processes (Stephanou & Mpiontini, 2017; Xu et al., 2017):

Metacognitive knowledge involves what individuals know about their own cognitive processes. It includes knowledge about personal cognitive strengths and weaknesses, understanding of specific tasks, and awareness of strategies that can be employed to facilitate learning. Metacognitive knowledge is often categorised into three types:

- Declarative Knowledge: Understanding of one’s abilities, skills, and intelligence, as well as knowledge of strategies and content.
- Procedural Knowledge: Knowing how to use strategies effectively.
- Conditional Knowledge: Knowing when and why to use certain strategies in specific contexts

Metacognitive regulation refers to the processes used to control and manage learning activities and involves:

- Planning: Deciding on strategies and setting goals before undertaking a task.
- Monitoring: Keeping track of one's understanding and performance during the task.
- Evaluating: Assessing the outcomes of the task and the effectiveness of the strategies used

Through developing metacognitive knowledge and metacognitive regulation, engineering students can become more effective problem solvers, capable of tackling complex challenges with confidence and competence. However, tertiary assessment regimes and practices often present students with simple problems in high-stakes, or pressure, situations, e.g. final examinations. This causes students to focus on obtaining the ‘correct’ answer to such problems, rather than evaluating the cognitive processes involved in formulating their approach to tackle the problem, assessing the knowledge or skills that might be required, and reflecting on the execution of the process of problem solution. This lack of awareness can hinder future learning and is therefore important for educators to address.

Engineering educators can help engineering students effectively develop metacognitive skills through a combination of informal learning activities, structured interventions, and self-reflection (Cunningham et al., 2016). In this study, activities aimed at improving the metacognitive abilities of engineering students, through both prediction (pre-activity) and reflection (post-activity) tasks over the course of a semester, were implemented and evaluated in a third-year electrical circuits subject as part of a Mechatronics Engineering undergraduate program. In this subject, students had previously struggled with identifying and defining the problems to be solved and had expressed difficulty in being to articulate their approaches to solving circuit problems. Interestingly, this was evident both in students who generally obtained the correct solutions and those who did not, and typically led to poor performance on the final examination for the latter. As the subject is a core requirement for several degrees, and rapidly builds upon scaffolded knowledge, it was seen as imperative to put activities in place to enhance students' awareness of their own cognitive processes, their ability to monitor and regulate these processes, and their strategic approach to learning and problem-solving. This paper will report on the approach taken for the initial run of these activities and report on some preliminary results, with more comprehensive data being gathered in a second iteration for more detailed analysis.

Approach

In addition to three one-hour lectures per week that cover the fundamental theory, the subject runs weekly, two-hour ‘workshop’ classes that involve a mixture of practical, laboratory-based activities and problem-solving sessions over the course of the semester. The problem-solving workshop sessions, in which students work both individually and collaboratively on sets of problems covering particular topic areas, occur in Weeks 3, 5, 8, and 10 of the 12-week semester. Typically, students would work through the problem sets at their own pace, some individually, and some collaboratively, and request help from a demonstrator if needed.

Two methods were employed to develop students’ metacognitive skills in the subject (Cunningham et al., 2016; Zimmerman, 1989):

- *Structured metacognitive interventions*, through classroom activities to promote metacognitive development. These activities help students become more self-aware and practice metacognitive regulation, improving their ability to Plan, Monitor, and Evaluate their learning processes.
- *Self-reflection and awareness*, where students are required to engage in self-reflection about their learning processes. This involves understanding what they know, what they do not know, and how they learn, facilitated through self-assessment exercises.

The three problem-solving workshops in Weeks 3, 5, and 8, covering analog electronics concepts, were the focus of the metacognitive activities. In the first of the three problem-solving workshops, students were given some brief instruction on metacognition and the Planning, Monitoring and Evaluation steps of the problem-solving approach that would be used throughout the semester. In each of the three problem-solving workshops, students were presented with five example problems to work on, one at a time, which focused on applying knowledge of electrical circuits for performing circuit analysis and applying circuit solving techniques introduced in the lectures. Each problem was completed, in turn, by completing predictive (Planning), problem solving (Monitoring) and reflective (Evaluating) activities, in that order.

Predictive activities (Planning)

After reading over the problem statement, students were requested to:

(a) rate the problem's perceived difficulty on a scale of 1 to 10, with 1 being 'extremely simple' and 10 being 'extremely difficult';

(b) from a given list, select the concepts that might be necessary to understand and/or circuit-solving techniques used in order to solve the problem;

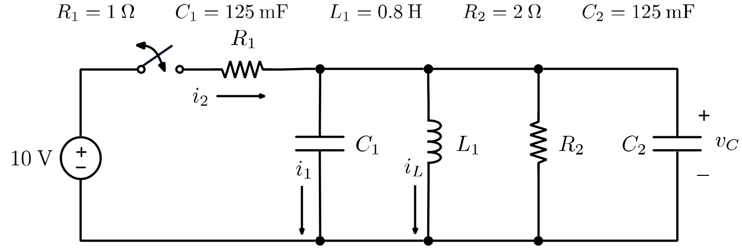
(c) write down the steps they will take to solve the problem, drawing upon the concepts and techniques they selected in (b); and

(d) identify where or how a misconception or mistake might occur in the steps listed in (c).

Students were given three minutes for this process, irrespective of the perceived difficulty of the problem, and were not permitted to start work on the problem until this time had elapsed. As this was the initial run of the activities, student responses were kept anonymous in order to encourage more accurate reporting without fear of their subject marks being affected by their responses. Figure 1 shows an example problem and the questions related to the Planning phase.

In the circuit shown below, a switch is connected between a DC voltage source and a network of five passive devices with the following component values:

$R_1 = 1\,\Omega$ $C_1 = 125\,\text{mF}$ $L_1 = 0.8\,\text{H}$ $R_2 = 2\,\Omega$ $C_2 = 125\,\text{mF}$



The switch is in the **open** position before time $t = 0$. At time $t = 0^-$, there is no energy stored in either capacitor, and the inductor current is given to be $i_L(0^-) = 1\,\text{A}$.

At time $t = 0$, the switch is instantaneously moved to the **closed** position.

Derive a differential equation for the voltage $v_C(t)$ for $t > 0$.

Planning (3 mins)

(a) What is your rating of the problem's difficulty, on a scale of 1 to 10, with 1 being 'extremely simple' and 10 being 'extremely difficult'?

(b) From the list below, select the concepts that might be necessary to understand and/or circuit-solving techniques used in order to solve the problem.

(c) Write down the steps you will take to solve the problem, drawing upon the concepts and techniques you have selected in (b). Make sure you number the steps.

(d) Where could a misconception or mistake potentially occur in you executing the steps listed in (c)?

Figure 1: Example question presented to students (concepts list omitted for brevity)

Problem solving (Monitoring)

After completing the predictive activity, students individually worked through the given problem, ensuring that they clearly wrote down all of their steps and working in solving the problem. Students were given an amount of time roughly proportional to the lecturer's perceived difficulty of the problem, of between three to ten minutes, similar to the way in which exam questions are constructed and accounted for. If students finished before the allocated time, they were asked to sit quietly and wait. Any students still working when the time expired were told to stop where they were and move on to the next stage.

Reflective activities (Evaluation)

After they attempted the problem, students were asked to reflect on their approach, with particular reference to their responses to the predictive activity for the given problem. Specifically, students were requested to:

(a) highlight where the concepts they identified earlier were being used in their working steps, and if not used, why not;

(b) rate the problem's (now experienced) difficulty on a scale of 1 to 10;

(c) reflect on whether they followed the planned steps; and

(d) estimate their confidence terms of their approach for constructing a correct solution given a similar problem (this was asked as a percentage, with 100% representing 'full confidence' and 0% representing 'no confidence at all').

After three minutes, a worked solution provided by the subject lecturer was shown to the students. They were then given a further two minutes to:

(a) identify which concepts were being utilised by the lecturer in the example solution;

(b) rate the problem's difficulty on a scale of 1 to 10;

(c) identify if their approach differed to the lecturer's; and

(d) identify if they had made any mistakes or misconceptions in their solution.

A short class discussion ensued, where students would explain some of their responses, before moving on to the next problem.

Post-semester survey and focus group

At the end of the semester, students were asked to complete an anonymous survey asking them to reflect on the problem-solving activities by rating their overall usefulness and the perceived value to their learning of both the subject material (knowledge) and the engineering problem-solving process (Human Ethics Project ID 31046). Twenty-four out of ninety-six enrolled students completed the survey. A focus group was held post-semester, after students had sat the final exam and received their marks, to get qualitative feedback on the activities. Five students were part of the focus group.

Results

In the initial problem-solving workshop class, students were surveyed using electronic polling software on their experience with using a metacognitive process when solving short answer problems such as the Planning, Monitoring and Evaluating approach described to them in class. Only 12% of students responded that they "use a repeatable, structured approach" that "involves both planning and reflective stages" in addition to the monitoring (problem-solving) stage when attempting such problems. This is not surprising as often the problems they have encountered thus far are perceived as being simple enough not to require a structured approach, particularly in terms of an initial Planning stage. In the end-of semester focus group, several students pointed out that before completing the metacognitive activities, they originally believed that an Evaluating stage would "not be necessary if they achieve(d) the correct solution"'.

Table 1 shows the mean scores for statements relating to the metacognitive activities in the problem-solving workshops on the end-of-semester survey, rated on a 5-point Likert scale, where 1 represents 'Strongly Disagree' and 5 represents 'Strongly Agree'.

Table 1: End of semester survey results (N= 24), 5-point Likert scale, 5 = ‘Strongly Agree’

Statement		Mean
The metacognitive activities in the workshop classes:	Provided me with valuable feedback on my knowledge	4.12
	Helped me to solve problems more efficiently over time	4.23
	Improved my ability to judge the difficulty of a problem	4.51
	Improved my ability to identify the concepts / techniques needed to solve the problem	4.21
	Helped highlight and/identify where I could potentially make errors	3.66
	Helped me identify which concepts I need to focus my study more on	3.92
I will continue to use the Planning, Monitoring, Evaluating approach to solving problems in the future		3.47

Overall, students were strongly positive about the activities improving their ability to judge the difficulty of a problem. They also largely agreed that the activities provided them with feedback on their knowledge of electrical circuits and improved both their ability to judge the difficulty of a problem and to find the appropriate concepts or process in order to solve the problem. However, it seems that their ability to highlight where errors could be made and which concepts they needed to focus on more, while still seen positively, were not as strongly affected. Focus group participants largely agreed that it was “difficult” for them “to guess where [they] would make errors without knowing what the solution is”. Questioned on why this was the case, all agreed it was down to “lack of experience”. Most stated that often the first thing that they listed was “calculation mistakes” as these could happen in any context but having them predict what other things could happen ahead of time, such as misinterpreting the question or incorrectly applying a circuit solving technique was seen as “extremely difficult” without having tried the question. One student mentioned that when exam questions are broken down into sub-questions it “gives them an idea where the mistake points could be”.

Focus group participants agreed that they tended to overestimate predicting the amount of concepts required to solve a problem, largely due to uncertainty with what might come up when solving the problem; however this gap appeared to close over time. This was due to them becoming “more confident in estimating what was needed ” as their experience grew, particularly “when [they] saw how the lecturer was thinking with their solutions”. One issue mentioned was that some students felt they “took the wrong approach”, even though they solved the problem correctly, due to using a different circuit-solving technique to the lecturer. However, this was because most of the problems were able to be solved in a number of ways and the lecturer was not able to show all possible methods. It was pointed out to the focus group that the Evaluating stage is still important, as there might be a good reason not to take the approach that they did, even if it did produce a ‘correct’ answer. To better illustrate this, it was suggested that students who took different approaches could compare and contrast what they did as part of the Evaluating stage as a future peer-based activity.

Notably, students were more reserved about continuing to use the Planning, Monitoring, Evaluating approach in the future, which achieved the lowest mean score in Table 1. This might be due to the survey statement being somewhat ambiguous about in what context, or where, they might imagine they could use the approach. A more focused question in the context of electrical circuits or electronics might yield more positive results, as when this was asked of the focus group, students unanimously agreed that they would apply it to their future circuits subjects.

Discussion

The data gathered as part of the problem-solving activities indicated that it was valued by the students and improved aspects of their metacognition. However, as this was the initial run of the project, limited data were able to be published due to the student problem sheets not having ethics approval at the time of completion. Additionally, these sheets were completed anonymously and therefore individual students were not able to be tracked over time.

There are some recognised challenges in measuring the effects of the metacognitive activities. Firstly, student self-reporting can be subjective, as it relies on the student's self-perception and ability to articulate their thoughts. This can be variable, even among a discipline-focused subject cohort. Secondly, while questions for the problem-solving sessions were carefully selected, metacognitive abilities can still vary depending on the context and type of task, making it challenging to generalise results. In the future, it is hoped that a larger number of students will participate in the surveys and volunteer for the focus group in order to more broadly represent the cohort.

Future work

The initial run of the project has pointed to many interesting directions in terms of future work. Firstly, it would be instructive to track students' metacognitive skills development over the course of the semester to look for longer term improvement, which necessitates students providing a unique identifier on their response sheets.

It was noticed in-class that while students typically initially took the whole three minutes to complete the Planning stage, as the semester went on many had finished before the deadline and were waiting for the next stage. It would be illuminating to formally measure their completion time and investigate whether this decreasing phenomenon holds for the majority of the students, potentially indicating improved metacognitive skills in terms of planning. The existence of any correlation between the perceived difficulty of the problem (during the Planning phase) and the time taken for completing the Planning stage would be worthwhile to explore.

The next iteration of the activities will research several of these directions, amongst others, and provide a more comprehensive data analysis of the completed student problem sheets.

Conclusion

Metacognition plays a crucial role in learning and academic success, as it allows students to become more effective learners by understanding how they learn best and by employing strategies to enhance their learning process. The problem-solving workshop classes implemented in the subject provided targeted activities associated with a set of circuits problems that required students to plan, monitor, and evaluate their problem-solving approaches in order to build and improve their metacognitive abilities. Initial evaluation has shown students reporting a positive effect on these abilities and suggests that engineering educators should incorporate such activities into their curricula. Future work is planned that will disseminate more detailed data on how the effect is manifesting itself in how students learn, solve problems and make decisions, leading to them becoming more effective learners.

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