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Instilling problem-solving competence in undergraduate engineering students

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CONTEXT

One thing that all types of engineers have in common is that they are expected to solve unfamiliar, complex problems. Although the development of problem-solving skills are generally implied throughout undergraduate courses, employers complain that engineering graduates are not meeting their problem-solving expectations. Explicit development of problem solving skills within undergraduate engineering degrees may help to bridge this gap.

PURPOSE

The broader study in which this work-in-progress paper is located explores how the teaching and learning of undergraduate mathematics can instil problem-solving competence in engineers. This paper develops the theoretical framework for developing, implementing and assessing a pilot problem-solving unit, arguing that engineering mathematics modules offer advantages as a home for a unit to explicitly teach problem-solving.

METHODOLOGY

A pilot problem-solving unit will be implemented, reviewed and adapted within a second-year engineering mathematics module. Data collection methods include interviews with students to understand their views of problem solving and observations of students' interactions with the problem-solving unit activities and materials. Analysis of qualitative data will inform improvements needed in problem-solving skills and the facilitation of these skills to engineering students within the context of undergraduate mathematics modules.

ANTICIPATED OUTCOMES

A working definition of problem solving has been summarised from literature and this definition can guide the measure of impact of the planned intervention. The anticipated results of the intervention study are that direct problem-solving skills learning can be facilitated as part of an undergraduate course at university, and that mathematics courses offer a sound framework for these skills to be successfully taught to engineering students.

CONCLUSIONS

The literature on problem solving indicates that problem solving skills can be developed and that these may need reinforcement over time and in different contexts. This research will provide support for the claim that the abstract context of mathematics courses may be helpful in developing transferable problem-solving skills in engineering students. Further research can explore whether a problem-solving unit is necessary for engineering students to be competently qualified and if the appropriate place for a problem-solving course to be implemented is within an undergraduate mathematics course. Furthermore, good practice between universities will help to develop students as competent problem solvers and ready to solve problems upon graduation into the profession.

KEYWORDS

Problem-solving, engineering, mathematics, graduate outcomes

Introduction

According to dictionary definitions of engineering, the outputs of an engineer involve the creative application of science and mathematics (Smith, 2021), as well as “the design and manufacture of complex products” (Merriam-Webster, 2021). How does the engineer achieve this? Engineers achieve their outputs through continuous, creative problem-solving.

Problem solving is a skill that is developed throughout a lifetime. However, employers of engineering graduates want team members who can competently deal with the frequent problem-solving challenges they will face (Haron et al., 2019; Wolff, 2017). Graduates with robust problem solving abilities seem more likely to be employed, and to be satisfied with their contributions to the engineering workplace.

Background to research

To give a bit of background to how the need and idea for this research came about, some background on the first author is given. Privileged to have received one of the best education in engineering on offer in South Africa, she started her career as an industrial engineer in South Africa and in Zambia. Interestingly, she and her engineering graduate colleagues felt incompetent to practise as new engineers and to immediately add the value expected of them. There was a perception in the workplace that feeling incompetent is not unexpected and that graduate engineers are hired for the ability to think and solve problems, not necessarily for their technical know-how. The motivation for this study is directed by the broad question, how can undergraduate engineering students be best educated to contribute to industry upon graduation?

Problem Solving in Mathematics

Much of the work carried out on mathematical problem solving draws on decades of work by George Pólya. He emphasises the importance of action in describing problem solving as, “To search consciously for some action appropriate to attain a clearly conceived, but not immediately attainable aim” (Pólya, 1962, p. 117). Liljedahl et al. (2016) confirm and conclude that the activity of mathematics is to solve problems. Reflecting on their activities while problem solving helps to develop problem-solving skills for the future and is the last step in Pólya’s (1945/2004) broad-brush heuristics for the problem-solving process: (1) understand the problem, (2) devise a plan, (3) carry out the plan and (4) look back.

Badger et al. (2012) suggest that a mathematical problem is a question whose procedure for attaining an answer is uncertain. It is worth mentioning that a mathematical problem is not necessarily experienced in the same way by two people. One person’s knowledge and experience will differ from another, hence one person’s routine question might be another person’s problem. A mathematical problem is thus audience dependent. A certain group of students in a first-year undergraduate mathematics module will find something to be a problem, that second-year students should not find problematic anymore.

Students can’t learn how to problem solve unless it is established and known what they already know about problem solving. This statement is supported by David Ausubel’s dictum that what a learner already knows is the most important single factor that influences learning (Ausubel, 1968). Students are to learn how to grapple with problems to ensure that problem solving activities are not a negative experience on the whole.

In undertaking problem-solving a student needs to develop both intellectual and temperamental qualities. Students need to (Badger et al., 2012):

Firstly, identify essential steps and work out a strategy.:

- Seek out relevant knowledge and bring it to bear.
- Use structured and logical arguments.

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- Carry through a plan accurately using a sequence of linked steps.
- Know when to turn back in a dead end and try a different tack.
- Organise, present, and defend their solution.
- Submit a solution to the scrutiny of the teacher or their peers.

Then explore the consequences of their solution, ask further questions, experiment with hypotheses and conclusions, try out generalisations.

Lecturers are critical in enculturating students into practicing problem solving by not presenting problem solving in a hidden curriculum (Bergenhenegouwen, 1987), but rather promoting and sustaining varied mathematical thinking. Rather than basing mathematics learning and teaching on memorized rules for computation, teachers need to be guided by the question: what do proficient problem solvers do as they solve increasingly complex problems? (Pólya, 2000). Students need to be put in unfamiliar situations with problems that are novel to them, but the expectation is that they must tackle the problem seriously on their own (Badger et al., 2012).

Paul Halmos (1980) sums up the importance of problem solving in mathematics by noting that problems are at the heart of mathematics, and that mathematics in its essence consists of problems and their solutions. Engineering prospectuses of South African universities have revealed that mathematics courses offer no explicit modules on problem solving, rather it is implied that problem solving skills will be acquired in these courses. This highlights the gap present in explicit problem solving skills instruction and further motivates the importance of this research.

A Problem Solving Definition

The following definition of problem solving is based on numerous descriptions and the first author's experience when working as an engineer, and is a starting point for this study on problem solving:

> The process of problem solving requires someone to take the initiative to undergo an iterative process of finding solutions to a difficult or complex issue (from the perspective of the problem solver), by firstly questioning the problem and the necessity and the validity of it and then creatively unpacking and defining the problem requirements, whether it be individually or collaboratively, matching requirements to known tools, thus coming up with an implementable, systematic strategy to implement a first solution to the problem(s), analyzing the effectiveness of the first solution(s), reworking the solution(s) if necessary and then implementing the final solutions. Problem solving requires the individual to not be risk-averse and to not be afraid of failing, but rather embrace the iterative nature of problem solving. It is also important to note that a clear vision of how the entire problem should be solved is not necessary at the start, rather one problem requirement should be solved at a time and 'bridges should be crossed' as and when the problem solver gets there.

Research Question

This research study addresses the research question: How can problem-solving skills be instilled in students within the context of an engineering mathematics module in a South African university?

Methodology

The literature on problem solving in mathematics supports the plan to develop, implement, review and adapt a virtual pilot problem solving unit as part of a mathematics module at the University of Cape Town. A qualitative action research study will inform improvements

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needed in students' problem-solving skills and the facilitation of these to engineering students within the context of a second-year undergraduate mathematics module. The first author will facilitate a problem-solving unit within the course convened by the second author. Action research (McNiff, 1988/2013) and reflective thematic analysis (Braun & Clarke, 2020) are suitable methodologies for this research due to the involvement of researchers as participants.

Action research is defined as "a disciplined process of inquiry conducted by and for those taking the action" (Sagor, 2000, p. 3). The purpose of using action research as the primary research method for this research is to develop an intervention suitable to the context and responding to the actual rather than perceived needs of the participating students and lecturers. The method is feasible as access to students and lecturers in a mathematics module for engineering students is available, which allows for good quality primary data to be collected.

The problem-solving unit will be implemented in a second-year Vector Calculus Course with one contact session per week for three weeks. The contact time will be done virtually during the students' tutorial time. In order for students to engage properly with the problem-solving unit, the successful completion of this three-week unit can replace their lowest two tutorial marks in the semester. Before the implementation of the problem-solving unit, an initial interview or questionnaire would be conducted with each participant individually and these results compared with a final interview or questionnaire conducted at the end of the unit.

During the problem-solving unit, data collection will include individual and small-group interviews, voice recordings of students during problem solving tasks, and reflection of observations of students. This data will be transcribed and analysed by means of Reflexive Thematic Analysis using the software NVivo that streamlines this process. The analysis process will follow the below iterative process (Braun & Clarke, 2020):

Phase 1: Data Familiarization and Writing Familiarization Notes

Phase 2: Systematic Data Coding

Phase 3: Generating Initial Themes from Coded and Collated Data

Phase 4: Developing and Reviewing Themes

Phase 5: Refining, Defining and Naming Themes

Phase 6: Writing the Report

Due to the current, global COVID-19 pandemic, the implementation of the pilot problem solving unit as well as the data collection will need to be done virtually. Locating the study in a mathematics module will open participation to students from all engineering departments. The success of the pilot project relies on the buy-in of the faculty and students that are part of the study.

Each aspect of the problem-solving definition developed in the theoretical framework will be used as an indicator of problem-solving ability. Tasks in the problem-solving unit will be designed to draw on all aspects of the problem-solving definition. The definition will also be a standard against which to assess students' problem-solving abilities. The indicators of problem-solving ability could thus be defined as:

- Problem solving is performed as an iterative process.
- Students feel confident in their ability to solve problems and therefore feel confident to take initiative to tackle a problem.
- The necessity and the validity of the problem needs to be questioned at the outset.
- The goal of problem solving is to find solutions to issues that are difficult or complex from the perspective of the problem solver.
- Problem solving is a creative process.

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- Problem solving can be done individually or collaboratively.
- To understand a problem, a problem needs to be unpacked and problem requirements defined.
- Problem requirements need to be matched to known tools to solve the problem.
- An implementable strategy needs to be developed to solve the problem(s).
- Once the first solution is implemented, the effectiveness of it needs to be analyzed.
- The solution(s) need to be reworked if necessary and then implemented again.
- Problem solving requires the individual to not be risk-averse and to not be afraid of failing, but rather to embrace the iterative nature of problem solving.
- A clear vision of how the entire problem should be solved is not necessary at the start of the problem-solving process, rather one problem requirement should be solved at a time and 'bridges should be crossed' as and when the problem solver gets there.

Limitations

The limitations of this study prevent the results from being broadly generalised to all engineering students and contexts. The rich data collected from this small-scale qualitative data will allow for a close interrogation of students' problem-solving abilities, however the data in the first action research cycle will only be gathered from one class in one engineering mathematics module at one university. The subsequent action research over different semesters will involve different students, and the participation of future students and convenors cannot be guaranteed. Having a history of high achievement, and despite assurance that there will be no penalty to grades for participating, students may give what they think the 'right answers' are in interviews, which may contradict observation data.

Conclusion

The anticipated results of this study are that a need for direct (as opposed to implied) problem-solving skills learning exists for engineering students; direct problem-solving skills learnt through methods based on social constructivism (which furthermore builds students' effective communication and teamwork skills) can be facilitated as part of an undergraduate course at university; and finally that mathematics courses offer a sound framework for these skills to be successfully taught to engineering students.

Engineering students need to be confident in their problem-solving skills in mathematics modules, in their future modules and in the workplace. Furthermore, good practice between universities needs to be shared in this regard to maximise the ability of graduating engineering students to be competent problem solvers and ready to solve problems upon graduation into the profession.

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