Promoting Problem Solving through Explicit Teaching and Assessment

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***Abstract**: The engineering profession in Australia has taken a leading role in promoting generic capabilities of engineering graduates [1]. Since that time, Australia's three peak employer organisations have urged all education systems to enhance these skills through their programs [2, 3]. Past efforts to promote generic skills [4] have foundered partly because no viable mechanism was established to link the development of these capabilities to the content and processes of teaching within disciplines.*

In this paper, we describe an approach to promoting problem solving in two topics in the first year of an engineering course. We describe the use of an assessment tool and some support materials for students and a process that used self-assessment followed by lecturer validation to grade student achievement in problem solving. We present the results of analyses of data gathered using the assessment tool.

Engineering students at Flinders University undertake two topics in their first year, Circuits and Devices 1 and Digital Logic Design (one quarter of their studies), that start their technical education in electrical and electronic circuit theory. These topics provide both theoretical and practical skills in the analysis, use and design of electrical circuits, both analogue and digital, based on the operation and properties of their constituent devices. In addition to these technical topics, students also undertake Team Project and Communication Skills, a topic whose aim is to develop a range of transferable skills including engineering project planning and design, oral and written communication skills, and group-work skills.

One of the many difficulties associated with teaching first year engineering students is an apparent lack of problem solving ability when dealing with challenging technical questions. They do not seem able to extend the knowledge learnt in their course to new problems.

Many engineering educators have sought to develop generic capabilities in their students. Recent examples include Patrick and Crebert [5] and Johnston and McGregor [6]. In this study, we used a problem solving skills assessment tool that had been developed and trialled in an earlier study [7]. We provided students with a range of support materials[1] designed to explain what generic capabilities were and why they were valued by industry. The materials also included an explanation of the model of problem solving that we implemented in this study. Importantly, we required students to assess their own problem solving performance using the assessment tool before submitting their assignments. Their assignments were marked as they had been in previous years, and in addition, their lecturer assessed explicitly students' problem solving performance using the assessment tool.

[1] Copies of the Problem Solving Skills Assessment Tool and support materials are available from David Curtis (david.curtis@flinders.edu.au).

Method and Rationale

From Theory to Practice

Like all generic capabilities, problem solving is a complex activity. Much research effort has been directed at understanding this phenomenon over the past century and several major theoretical perspective have emerged [8]. Much of the research on problem solving has involved comparisons between novice and expert problem solvers [9]. Novices and experts differ along several important dimensions. The most important difference is that experts have highly developed knowledge bases built upon solutions to previously encountered problems. They have developed schemas that enable them to classify problems according to fundamental principles of their disciplines. Experts bring their extensive knowledge to bear in understanding and solving new problems. By contrast, novices, who lack this extensive knowledge base, must rely upon generally applicable processes as they attempt to solve problems. Novices tend to look at the surface features of problems, rather than look for underlying principles [10]. Their solutions are slow and error prone compared with those of experts. While the differences between novices and experts are important and informative about problem solving, the challenge facing educators is how to move students from their novice status to competence effectively and efficiently [11, 12]. The emergence of expertise is expected to take much longer than an undergraduate degree program. However, academic teachers will have done their job well if students become competent by the time they graduate and are on a trajectory that will take them to expert status if they are able to learn from the experiences of professional practice in the discipline.

Two general theories of problem solving that have received substantial support over recent decades are general process models and theories of situated cognition. Process models are based on a computer analogy in which general processes are thought to be available and that problem solvers use specific variables from the current problem as inputs to the general procedures [13]. Situated cognition holds that the problem solving methods used by individuals are situation specific and are developed through repeated practice in particular situations [14, 15]. While both theoretical positions have been able to explain aspects of problem solving, both have their critics. Simon's own work on problem isomorphs [16] and other work on transfer [17] have shown that even when individuals know relevant general procedures, often they fail to implement those procedures when they are relevant. The examples used to support the case for situated cognition, for example making choices among alternative products while shopping, lack the depth of knowledge and complexity of judgement required in professional practice. Further, the situations are those in which the subjects were highly experienced and could be considered experts. Because it is observed among experienced practitioners, problem solving as described within the situated cognition framework does not provide an explanatory mechanism for the passage from novice status through competence to expertise.

In the present study, we took the view that novices in engineering require a model of problem solving that would guide them through solutions to the problems they encounter routinely in their course. In particular, we theorised that problem solving was itself a body of knowledge that students needed to internalise in parallel with the engineering knowledge they were developing. The knowledge of problem solving is of several kinds. First, there is a component of declarative knowledge and we needed to provide students with an accessible account of what problem solving is. Second, we took a procedural view and argued that problem solving could be characterised as a series of related processes. Several alternative accounts of problem solving processes are available, and we based our model on the work of Bransford and colleagues [18, 19]. Third, we incorporated the concept of metacognition in that we wanted students to be aware of their performance, particularly in monitoring their work and reflecting on it. Fourth, we accepted the position advanced in situated cognition that learning and problem solving are located within particular contexts and that students needed to learn problem solving in authentic contexts provided by their learning in engineering. The assessment tool and process that were employed embody these four propositions.

The Problem Solving Skills Assessment Tool

The Problem Solving Skills Assessment Tool that was used in this project is a modified version of one developed in an earlier pilot project [7]. In the development of that tool, the process approach to problem solving that we employed was based on the work of Bransford and Stein [19]. They identified five fundamental problem solving processes, namely identify the problem, define the problem, explore alternative solution strategies, apply the selected strategy, and look back over the solution. Other theorists have distinguished fewer or more fundamental processes. However, the differences have more to do with whether certain elemental processes are aggregated or not. For example, Polya [20] described understanding a problem as the first of four processes. This corresponds to the first two processes listed by Bransford and Stein. The five processes labelled by Bransford and Stein were modified to: define the problem, plan an approach, execute the plan, monitor progress, and reflect on the result. The first two Bransford and Stein processes were combined, while their final process, look back over progress, was split into monitoring and reflection. We believed that specific attention to reflection was warranted because this involves both looking back at the efficiency and effectiveness of the solution strategy, and anticipating future scenarios in which the method that has been used might be valuable. We theorised that reflection is part of the mechanism by which experts have laid down their knowledge base and built their internal expert system.

In order to make the five processes explicit, a set of indicators was developed for each process. Each indicator was a behaviour that the student could identify as one that they had enacted, or not, in their solution attempt. Finally, for each indicator, from two to four performance levels were articulated. The number of performance levels for each indicator was selected after consultation with teaching staff involved in the pilot study. Not only had the levels to represent fully the range of performances likely to be elicited for that indicator, but they had to be readily discriminable so that performance judgments could be made quickly.

In summary, the assessment tool embodied five main problem solving processes. Each process was articulated as a set of behavioural indicators, and the indicators had from two to four levels of accomplishment expressed through performance criteria.

This analytic approach to the assessment of problem solving should not be taken to indicate that this generic capability can be dissected into a set of atomistic processes. Indeed, our position is that problem solving is a highly integrated set of processes that are engaged iteratively and recursively in competent practice. However, describing problem solving as a set of major processes and providing behavioural indicators of those processes was designed to make problem solving accessible to learners. Further, this work has been driven in part by a concern to establish whether problem solving ability can be assessed and reported according to verifiable psychometric standards.

The Assessment of Problem Solving

Assessment is seen as a key driver for the development of skill. In the past, a variety of approaches that have not involved explicit assessment has been taken to the delivery of generic capabilities. For example, it has been common to map a range of generic skills onto specific content areas; when students achieve the content objectives, it is assumed they must have mastered the implicit generic capabilities. However, this approach to the delivery and assessment of these skills does not require that explicit attention be paid to them. In the project, we used explicit assessment to focus students' attention on problem solving.

The assessment model can be characterised as performance assessment. Performance assessment is used to assess the application of knowledge in context. The context is provided by the routine assessment tasks of the course. Good performance assessment practice requires that learners be informed of the purpose of the assessment, the criteria that will be used to make judgments and the levels of performance that will be deemed adequate [21, pp. 227-279]. These criteria were met by providing students with the assessment tool and detailed explanations of how the tool was to be used.

In order to engage students as much as possible in the assessment of problem solving and to enhance their learning about problem solving, they were required to assess themselves using the problem solving skills assessment tool. Their completed forms were submitted with each assessment task and marks were allocated for their use of this tool. Boud [22] developed a case for using self assessment, arguing that the capacity for self assessment is critical to individuals' abilities to manage their future learning. He argued:

> By deliberately keeping assessment out of the hands of learners, we are denying them one of the essential tools – perhaps the essential tool – which enables them to become lifelong learners. [22, p. 43]

However, if the results of assessment are recorded in students' transcripts, the institution must be able to report achievement authoritatively. For this reason, we argue that problem solving performance must also be assessed by the academic responsible for the course. Students had been informed that the lecturer's judgment would be recorded. The assessment tool was designed so that the lecturer's judgement was recorded on the form submitted by students and was returned to them with their marked assignment. Thus, students received feedback on their performance and on the adequacy of their judgment of their own problem solving performance.

In summary, the assessment model developed in this project involved the explicit performance assessment of students' problem solving accomplishment. Students were required to assess their own performance. Their lecturer also assessed them. The feedback they received was about both the quality of their performance and the adequacy of their judgment of their performance. This dual feedback was intended to enhance students' problem solving performance and to improve their application of the performance criteria.

Organisation of the Research Project

Fifty-five students enrolled in the first semester topic and 53 in the second semester. At the beginning of the year students sat a 55 item multiple-choice generic skills test. This was modelled on the Graduate Skills Assessment [23]. The test comprised items on critical thinking, interpersonal understandings and problem solving with 16, 20 and 19 items respectively.

Early in each semester and just before the first assignment was set, students were given a folder of materials explaining the purposes of the project, providing information on generic capabilities, and including an explanatory letter and a participation consent form. The folder included copies of the problem solving skills assessment tool. At about the same time, and during a lecture, the lecturer modelled the use of the assessment tool using a tutorial problem as a case study. The lecturer nominated four assessment activities over the year as vehicles for the problem solving assessment. For each assessment activity, students undertook the assessed task, completed a self-assessment of their problem solving performance, and submitted both for marking. The lecturer graded the substantive assessment task and reviewed the evidence presented by the student for their claimed level of problem solving performance. The lecturer then used the assessment tool to record a judgment of the students' problem solving facility. Both the students' self-assessment and the lecturer's judgment on all criteria were recorded for analysis.

At the end of the year, the topic results for each semester were recorded. In doing this, students were de-identified by replacing their names with an ID code known to the lecturer but not the researcher, thus preserving confidentiality.

Analysis and Results

In most analyses for this project, the Rasch measurement model, implemented in the program Quest [24], was used. The Rasch model assumes that items used to assess performances are indicators of an underlying (latent) trait. Items are expected to reveal similar patterns of responses, reflecting that common trait, in this case problem solving ability. Further, the model assumes that responses to items are ordinal, rather than interval in nature. The Rasch model accepts as inputs ordinal responses to items and produces an interval scaled estimate of each person's ability on the trait. The method also tests the conformity of items with the assumption of a common trait and provides a range of summary statistics that enable the measurement properties of the assessment to be evaluated [25].

Generic Skills Assessments

The three scales of the generic skills test, interpersonal understandings, critical thinking and problem solving, were analysed using the Rasch measurement model in order to ascertain the conformity of all items with the intended construct, to generate estimates of item difficulty and to assess the measurement error. On all three scales, items showed good fit. Summary statistics for the scales are shown in Table 1. The interpersonal understanding scale showed a low person separation index and this is attributed to this group of participants finding the items rather easy. The remaining generic skills scales showed acceptable to very good measurement properties.

Table 1: Summary statistics for scales of the generic skills test

Scale	Number of items	Item separation reliability	Person separation reliability	Cronbach alpha
Interpersonal understanding	20	0.75	0.41	0.75
Critical thinking	16	0.90	0.64	0.79
Problem solving	19	0.96	0.73	0.80

Using the Rasch estimates for items, scaled scores were computed for each candidate.

Problem Solving Skills Assessments

The problem solving skills assessment instrument was calibrated using the lecturer's judgments. One item, which referred to the modification of given strategies, was found not to conform to the response pattern of other items and this item was removed from subsequent analyses. This item had been included in order to maintain consistency with a previous Australian generic skills scheme, the key competencies. In that scheme, levels of performance had been distinguished based on students' self-direction of their problem solving performance. The measurement properties of the instrument were quite good, with an item separation reliability of 0.93, a person separation reliability of 0.89 and a Cronbach alpha of 0.90. Problem solving ability estimates were produced for each candidate for the three occasions on which the assessment tool was used based on both the candidates' self-assessments and the lecturer's judgment.

The most difficult items for students prompted them to provide evidence that they had reflected on the efficiency of their solutions, had compared the current problem with previous ones, and had anticipated situations in which the approach being taken in the current problem could be applied in future. These items all tap a reflective learning dimension. Few students were able to provide evidence of these activities, and those who did were high achievers. Reflective behaviour is implicated in effective learning and is thought to be one of the mechanisms by with experts build their complex knowledge bases. The students in this study are novices and few, even when prompted, engage in this important learning behaviour. A related item asked students to provide evidence that they had recalled relevant or similar problem tasks in planning their approach to the current problem. This item also was found to be difficult for these students. It is a corollary of the reflection items. If students do not lay down a memory trace of effective problem solving strategies through reflective behaviours, there is little prospect that this knowledge will be available to guide future problem solving performances.

A comparison of the students' self-assessments with the lecturer's judgments showed that students rated themselves slightly better than their lecturer did, but that during the year the ratings of students and the lecturer became more similar. However, over the year there was no statistically significant growth in problem solving ability. Students' self-ratings showed a slight gain, but the lecturer's judgment remained relatively constant. It is worth noting that the problems undertaken by students later in the year were more complex than those presented early in the year were.

Influences on Final Marks

In order to assess the influence of students' generic skills problem solving and critical thinking abilities as assessed at the beginning of the year and their problem solving facility through the year on their final mark, a simple path model was tested using AMOS [26]. Because there had been no statistically significant growth in problem solving performance scores over the year, the mean problem solving score over the three occasions was computed. The model, including estimated path coefficients, is shown in Figure 1.

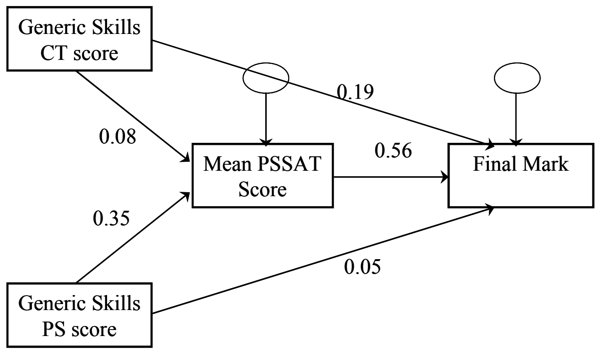

Figure 1: Path diagram showing influences of initial generic problem solving and critical thinking abilities on mean problem solving assessment over the year and on final mark

The moderate path coefficient (0.35) from initial problem solving score to the process based problem solving assessment mean score suggests that both forms of assessment tap common elements, but that the process based approach does assess some unique components. The weak relationship (0.08) between critical thinking and problem solving assessment indicates that they represent quite different cognitive processes. The stronger relationship (0.56) between the process-based problem solving assessment score and the final mark for the year suggests that the processes that underlie successful problem solving also contribute to academic success in mastering the knowledge and skills assessed across tutorial exercises, practicals, projects and examinations. Although there is a relatively weak path coefficient from the generic skills problem solving score to the final mark (0.05) the total effect attributable to the generic skills score is a moderate 0.25 (0.35 x 0.56 + 0.05). Critical thinking has a similar net influence (0.25 = 0.08 x 0.56+0.19) on the final mark for the year.

Conclusions and Implications

The problem solving skills assessment tool has quite good measurement properties. It appears to be a useful tool for the performance assessment of problem solving skills in and engineering context.

What has not been demonstrated is statistically significant growth in the problem solving facility of students over the course of the year. In part, this may be a result of the increasing difficulty of successive assessment tasks over the year. However, based on observations of students' practices another factor is also suspected, and that is the difficulty students experienced when required to assess their own performance. Self-assessment seems to be a task for which students are poorly prepared.

The observation that students did not engage in reflective learning behaviours suggests that greater attention needs to be directed to this aspect of their approaches to problems. It seems that students focus on the demands of immediate tasks without an appreciation of the broader purpose of each task in a longer term curriculum aimed at building a professional knowledge base. Students are under pressure to meet the demands of their courses and to balance these with work and social relationships. However, this observation suggests the need to encourage students to develop a 'helicopter vision' of their learning [27].

The process-based assessment of problem solving appears to have tapped some important cognitive processes that are also implicated in effective learning and performance on the tasks that are assessed routinely in the engineering curriculum. The reasonably strong relationship between process-based assessments of problem solving and final marks suggests it is worth persevering with the explicit teaching and assessment of problem solving processes. The arguments for self-assessment [22] are compelling. Perhaps it would be wise to introduce this initiative separately from the novel process-based approach to the assessment of problem solving.

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