The Allocation of Time Spent in Different Stages of Problem Solving: Problem finding and the development of engineering expertise

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SESSION S2: Educating the Edisons of the 21st Century

CONTEXT Four major steps of problem solving include understanding the problem, planning the solution/s, implementation and evaluation. Despite a significant body of research on engineering problem solving, it is unclear how the problem solving steps occur in practice and whether there are any differences in the approaches of engineers with varying industry experience.

PURPOSE The research questions investigated were: a) Based on the first 3 stages of problem solving process: i) Understanding the problem, ii) Planning, and iii) Implementation, what proportion of time is devoted by engineering practitioners to each step? and b) Does the time devoted to the different stages of problem solving change over the years in profession?

APPROACH A survey method was undertaken and 215 engineers with varied industry experiences as well as fields were involved in the study. The responses were then categorised based on different levels of industry experience from novice to experts. The data were analysed statistically with SPSS software.

RESULTS It was found that differences exist between the responses of the different groups of engineers. It was observed that there is a link between industry experience and the time spent at different stages of problem solving, especially in Stage 1 (Understanding the problem).

CONCLUSIONS A number of key findings are presented in this study. It was found that industry exposure is crucial for the acquisition of skills that are important for proper problem understanding. The study also provides the evidence that around 10 years of industry experience really formed engineering expertise. These findings have implication to the future development of educational strategies, including in the choices of the type of heuristics that may assist young engineers in developing their problem analysis skills more effectively.

KEYWORDS Engineering problem solving, development of expertise, problem finding, problem solving models

Problem solving models

One of the key defining models of problem solving was developed by Polya (1945) in his work on mathematics problem solving. Polya (1945) advocated that mathematical problem solving consists of four distinct steps: understanding the problem, planning the solution, implementation of the solution and finally, looking back. Carlson and Bloom (2005) evaluated problem solving behaviours of 12 mathematicians as they attempted to solve four mathematics problems. They discovered that the four-step problem solving process advocated by Polya is cyclic and proposed a more accurate framework of mathematical problem solving. In observing their expert subjects, Carlson and Bloom (2005) found that they engage in trial and error, oscillating between the planning and verification stages, until the solution is established. Specific to engineering, Belski (2002) proposed a seven-step process of engineering problem solving that was based on Systems Thinking. He recommended numerous heuristics that can be used at each step of the seven-steps process. Belski (2002) also believed that the problem solving steps are inter-connected.

Despite the differences in the models, all of them can be fitted into four key steps: (Stage 1) understanding the problem, (Stage 2) planning, (Stage 3) implementation and (Stage 4) evaluation. A summary of the three problem solving models discussed above is presented in Table 1.

Table 1: Problem solving models

	(Polya, 1945)	(Carlson & Bloom, 2005)	(Belski, 2002)
Stage 1: Understanding the problem	1) Understanding the problem	1) Orienting: sense making, organising, constructing	1) Situation analysis 2) Revealing the system's stage of development
Stage 2: Planning	2) Developing a plan	2) Planning: conjecturing, imagining, evaluating	3) Identifying an ideal solution 4) Idea generation
Stage 3: Implementation	3) Carrying out the plan	3) Executing: computing, constructing	5) Failure prevention 6) Adjusting the super-system and sub-systems in accordance with the solution found
Stage 4: Evaluation	4) Looking back	4) Checking: verifying, decision making*	7) Reflection on the solution and the process of the solution

* If solution is inaccurate, then return to stage 2.

The importance of understanding the problem

Recent studies found that Stage 1, understanding the problem or problem finding, is considered to be the most important stage in the problem solving process (Belski, Adunka, & Mayer, 2016; Harlim & Belski, 2013b). Newell and Simon (1972) also suggested that "when a problem is first presented, it must be recognised and understood" (p. 809).

Newell and Simon (1972) believed that problem solving relies on pattern recognition. Their theory relied heavily on the concept of the accumulation of knowledge and developing expertise. Experts resolve problems well as they have well-developed schemata (Gick, 1986; Kalyuga, Ayres, Chandler, & Sweller, 2003; Kalyuga, Renkl, & Paas, 2010). As experts are considered to be better problem solvers, there has been a number of investigations focusing on expert problem solving (Atman, Chimka, Bursic, & Nachtmann, 1999; Belski et al., 2016; Bilalic, McLeod, & Gobet, 2009; Carlson & Bloom, 2005; Chi, Glaser, & Rees, 1982; Gick, 1986; Gobet & Simon, 1996). The outcomes of such research can be used in educational settings to develop strategies that will facilitate the advancement of problem solving skills of novice engineers.

Reflection differences

The role of evaluation (reflection) in engineering problem solving is not explored in this paper. The process of reflection is utilised and perceived differently by novice and expert engineers (Harlim & Belski, 2013a). In addition, novices have the misconception that reflection is not necessary (Adams, 2010; Harlim & Belski, 2010). Therefore, this paper will only focus on the first 3 stages of problem solving: understanding the problem, planning and implementation.

Research questions considered

Two research questions are explored:

1) Based on the first 3 stages of problem solving process: i) Understanding the problem, ii) Planning, and iii) Implementation, what proportion of time is devoted by engineering practitioners to each step?
2) Does the time devoted to the different stages of problem solving change over the years in profession?

Methodology

A survey method was undertaken to evaluate the research questions and the data were analysed statistically with SPSS software. The survey was part of a larger study spanning the years of 2009 to 2011 investigating the factors that impact on engineering problem solving performance. Participants were asked to reflect on the distribution of time during their problem solving practice by responding to the following question:

> *Think back of ONE engineering problem that you had resolved recently. Please allocate how much time you spent on each problem solving stage stated below (in percentages out of a total 100, e.g., 30, 50, 20).*

In the questionnaire, it was specified that the problem solving stages include:

- Stage 1: Understanding the problem (diagnosing the problem)
- Stage 2: Planning the solution/s (identifying the possible solution/s, and planning the implementation
- Stage 3: Implementation of the solution/s

A total of 215 engineers responded to the question, including 167 male and 48 female engineers. Within those who took the survey, 144 were engineering students, 56 were professionals and 15 were academics. The engineers who were involved in the study came from a variety of engineering background including Aerospace, Automotive, Mechanical, Biomedical, Chemical, Civil, Computer and Network, Electrical, Electronic and Communication, Environmental, Industrial as well as Mechatronics.

The data were then segmented into different classification of expertise. It was observed that young engineers in the research fitted in two categories: Novice Class 1 (N1) and Novice Class 2 (N2). Professionals with more than 10 years of industry experience were classified as experts (E) using the work of Chase and Simon (1973) as well as Prietula and Simon (1989) as guides. They proposed that experts are those who have more than 10 years of experience in a specific field (Chase & Simon, 1973; Prietula & Simon, 1989). Those in between the novice and expert groups were classified as mid-level engineers (M). Table 2 summarises the division of the survey participants into categories.

Table 2: Summary of categories based on level of expertise

Classification	Years of full-time work in engineering
Novice Class 1 (N1)	0 years (Students and recent graduates with no industry experience in the engineering field)
Novice Class 2 (N2)	equal to or less than 5 years
Mid-level (M)	6-10 years
Experts (E)	over 10 years

In the final analysis, responses that did not yield 100% when each of the three allocation of problem solving stages were added up were treated as outliers and removed. An example of this is when an engineer indicated that he or she had allocated 60% to Stage 1, another 60% to Stage 2 and 50% to Stage 3. A total of 197 responses were included in the final analysis.

Findings

Table 3 and Figure 1 present the findings on how the engineers surveyed spent their time within the three problem solving stages.

Table 3: Time allocated by engineers to different stages of the problem solving process

Classification	Number of responses included in the analysis	Stage 1 (%)	Stage 2 (%)	Stage 3 (%)
N1	85	M=28 SD=14	M=38 SD=17	M=34 SD=20
N2	63	M=33 SD=14	M=36 SD=15	M=31 SD=16
M	22	M=45 SD=16	M=31 SD=11	M=25 SD=14
E	27	M=31 SD=18	M=34 SD=13	M=35 SD=19
TOTAL	197			

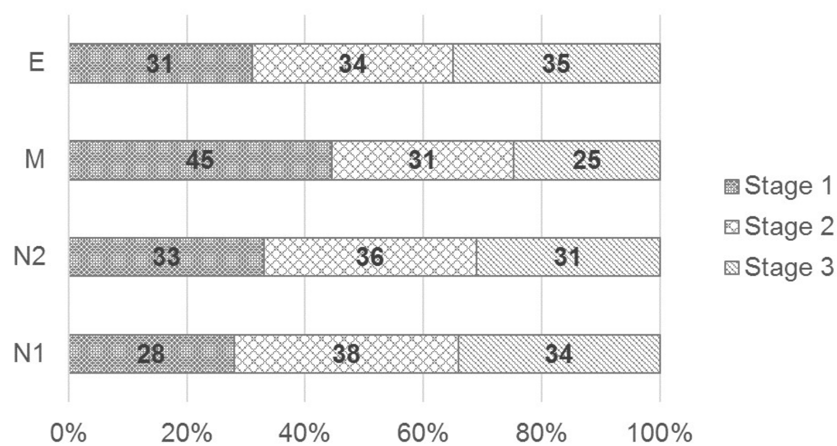

Figure 1: The proportion of time spent by engineers with different industry experience in the three stages of problem solving process.

Engineers with no industry experience (N1) spent the least time of the four groups in Stage 1 compared to the time spent on the other stages of problem solving (28% on Stage 1, 38% on

Stage 2 and 34% on Stage 3). The trend changed as the engineers gained industry experience. Although most of the time was still spent on the planning stage (36%), those with five years or less of industry experience (N2) reported spending more time on understanding the problem (33%) than on implementation (31%) in comparison to N1.

As the engineers gained 6 to 10 years industry experience (M), a clear reversal was observed. Most of the time was spent on Stage 1 with an average of 45%. 31% of time was spent on Stage 2 and 25% on Stage 3, indicating that in this group there is an obvious focus on problem identification. The engineers with industry experience of more than 10 years (E) reported spending less time on Stage 1 (31%) than on the other stages (34% on stage 2 and 35% on stage 3). The trend was similar to that of the N1 group, engineers with no industry experience.

Before investigating whether statistical significance existed in the responses of these groups, the Kolmogorov-Smirnov Test was carried out to determine the most suitable statistical test for the data obtained. Due to the violation of parametric assumption of normal distribution in the data, the non-parametric test, the Kruskal-Wallis Test, was used. Statistical significance was found between the groups only in their responses on how much time was spent in Stage 1, understanding the problem (p=0.000).

To determine where the statistical significance occurred in the data, the responses of each individual category for Stage 1 was tested in pairs using the Mann-Whitney U-Test. Time devoted to Stage 1 by the practitioners from the N1 and N2 groups did not differ much from that spent by the engineers from the E group. The difference in time devoted to Stage 1 between all other pairwise group combinations was statistically significant. The outcomes of the Mann-Whitney U-Test are presented in Table 4.

Table 4: Statistical analysis on group comparisons of time spent on understanding the problem

Comparison group	P-value
N1 – N2	0.020*
N1 – M	0.000*
N1 - E	0.445
N2 – M	0.005*
N2 - E	0.378
M - E	0.005*

*Statistical significance is observed (p<0.05 or p<0.01).

Discussion

The comparison of responses from the engineers with different industry experiences reveal an interesting pattern. The results from the two novice groups indicated that they are focused on the planning phase (Stage 2). The data from the mid-level group indicated a clear focus on understanding of the problem (Stage 1). Similar to the novice groups, the expert group reported spending more time in the planning stage.

Statistical significance was only observed within the data of Stage 1, understanding the problem, when the four categories of practical experience were compared. This suggests that the gain of professional experience mainly influences the way engineers conduct the problem diagnosis stage. In other words, statistically significant changes in time devoted to problem analysis over the years of professional practice suggest that acquiring advanced skills in problem analysis is paramount for gaining engineering expertise. This conclusion supports the idea that Stage 1 is an important aspect of problem solving performance (Belski et al., 2016; Harlim & Belski, 2013b). Therefore, this highlights that the key area of learning that should be focused on during engineering problem solving should be the problem analysis stage.

Statistical significance was also found when the responses of N1, novices with no industry experience, were compared to those of N2 (novices with 5 years or less of industry experience). This finding indicates that industry experience exposure leads to the realisation on the importance of problem identification for effective problem solving. This is also supported by the responses of the engineers in the mid-level group (M), those with 6-10 years of industry experience. The data reveals that industry experience between 6-10 years is the crucial period in the development of problem solving skills for engineers as a distinct focus on Stage 1 was observed. When the responses of the engineers in the M category were compared to all the other groups (N1, N2 and E), statistical significance was also found. The implication is that perhaps to discover how novices can be better problem solvers, there is a need to investigate what happens during these formative years.

The results of the survey indicate that as expertise is reached, the amount of time spent in Stage 1 decreases compared to those in the N2 and M groups. Literature in cognitive science has identified that experts are able to by-pass the search strategy when resolving problems due to their well-developed schemata which enable them to solve problems better and at a much quicker rate (Kalyuga et al., 2003; Kalyuga et al., 2010). Therefore, this finding is not surprising.

However, the data shows that both N1 and E groups spent the least amount of time in understanding the problem phase. It can be posited that these novices are behaving like experts when it comes to how they are spending their time in the different stages of problem solving. Much of problem solving studies have been conducted by the observation on how experts resolve problems. The outcomes of these studies were used to suggest how novices can learn to resolve problems from the strategies of their expert counterparts. This gives the assumption that when a novice behaves like an expert when solving a problem, he or she has truly become a good problem solver.

Although novices in this study devoted similar amount of time to Stage 1 as experts, they were unlikely to reach the problem comprehension of experts. As identified by Newell and Simon (1972), problem solving requires pattern recognition and the experts use of knowledge, stored in the long-term memory differs in experts and novices. Experts are better problem solvers due to the schemata they have in their long-term memory (Belski & Belski, 2008; Chi et al., 1982; Gick, 1986; Newell & Simon, 1972). When faced with situations to resolve, experts use these well-developed schemas to recognise the problems. Novices, on the other hand, do not possess knowledge schemas and need longer time to comprehend problems.

However, as exemplified in the data, novices emulate experts and do not devote adequate time to problem analysis. This study provides compelling evidence that this misconception by novices needs to be corrected. This may be addressed by teaching novice engineers more heuristics that focus on Stage 1 of the problem solving process. Some tools of the Theory of Inventive Problem Solving (TRIZ) can help novices to acquire the skills important for problem understanding (Harlim & Belski, 2015). Such heuristics includes the Size Time Cost Operator, the Notion of the Ideal Ultimate Result, the heuristic of Resources and the heuristic of Situation Analysis (Edisons21 Fellowship Team, 2016). In addition, strategies that expose them to industry conditions and situations can be considered to bring about the awareness of the need in spending more time in Stage 1.

In their research, Carlson and Bloom (2005) considered PhD candidates as experts in mathematical problem solving. Atman et al. (1999) compared the performance of senior versus first year students to gain insights on problem solving performance of experts. The difference between the responses of the engineers in the different categories, N1, N2, M and E strongly supports research findings that suggest that to achieve expertise, one needs 10 years or more of practical experience (Chase & Simon, 1973; Prietula & Simon, 1989). The results from this study show that a more stringent interpretation of expertise needs to be considered when designing studies on problem solving performance of engineering experts.

The implication is that there is a need to understand problem solving strategies of experts from the perspective of 'why' they resolve problems the way they do, rather than the mere 'how' or 'what'.

Conclusion

A number of key findings are presented in this study. It was found that professional practice is crucial for gaining the skills that are necessary for proper understanding of the problem. The data also revealed that this is the key stage that engineering educators should be focusing on in order to develop the problem solving skills of young engineers adequately. Novice engineers that participated in the research, especially those with no industry experience did not spend sufficient time understanding a problem, as they lack the awareness and have a misconception on how experts resolve problems.

The study also provides the evidence that around 10 years of industry experience really formed engineering expertise. The implication is that when designing studies on how experts resolve problems, a more stringent interpretation of expertise should be considered. The results also revealed that experience gained between 6-10 years in the industry may be the formative years in bringing about the realisation that understanding the problem is imperative for effective problem solving.

These findings have implication to the future development of educational strategies, including in the choices of the type of heuristics that may assist young engineers to develop their problem analysis skills more effectively.

The limitation of this study is that the data were collected retrospectively based on the engineers' perception on how much time was spent in each stage. Future research can investigate the research questions via proper observation or data collection during actual problem solving, using a non-self-reporting methodology. Future research can also investigate in depth how engineers with 6-10 years industry experience resolve engineering problems in practice. This will help to understand what happens during these years and may provide more insights on how novices can improve their problem solving skills.

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