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Problem Solving and Creativity for Undergraduate Engineers: process or product?

Jonathan Paul Adams jonathan.adams@northampton.ac.uk
Scott Turner scott.turner@northampton.ac.uk

The University of Northampton, Northampton, UK

Abstract **– Many researchers have written about the importance and complexities of developing problem solving skills and encouraging creative thinking and activity in engineering students.**
Whilst research suggests that established Problem Based Learning techniques are a suitable way for developing these skills it also acknowledges continued deficiencies in encouraging process skills as opposed to products or outcomes. This paper provides highlights of this previous work, and presents findings of action research in order to develop a module to improve and encourage process skills in engineering undergraduates. Lego Mindstorm robots have been used in the module to provide suitable practical activities and to stimulate student motivation.

Index Terms – Engineering Education, Problem Solving, Creativity, Learning Objects

Introduction

The ability to solve problems with a degree of creativity is highlighted as an essential characteristic for both novice undergraduate engineers and qualified engineering professionals in UK benchmark statements (Engineering-Council-UK, 2005; QAA, 2006).

The teaching of problem solving in engineering is highlighted in many texts. It is often suggested, however, that engineering education focuses heavily on problem solving skills, but that teaching in universities concentrates on teaching content rather than showing the processes involved in problem solving (Wankat and Oreovicz, 1992). Houghton proposes that problem solving is 'what engineers do' (Houghton, 2004). He contends that problem solving skills may be the most important thing we can teach our students.

It is possible to identify, from both anecdotal sources and more defined evidence, that deficiencies continue to exist in the teaching of problem solving skills, and that the traditional model of teaching used in engineering education may not provide sufficient motivation for engineering undergraduates (Chu and Lai, 2002; Felder, 2006) . These are confirmed by the authors' own experiences.

This paper proposes and describes action research to develop a problem solving and creativity module to address these issues.

Problem Solving – the challenges

There are many definitions of problem solving which include interchangeable concepts such as intelligence, learning, thinking and cognition (Mayer, 1992). Thus Johnson (1972) defined 'thinking' as problem solving, Sternberg (1991) 'intelligence' as problem solving and Soden (1994) 'learning' as problem solving.

Polya (1957) suggests that problem solving is based on cognitive processes that result in "finding a way out of a difficulty, a way around an obstacle, attaining an aim that was not immediately available". Woods, an engineering professor, offers this definition: "Problem solving is the process of obtaining a satisfactory solution to a novel problem, or at least a problem which the problem solver has not seen before" (Woods, 1977). Woods' definition shifts the focus from looking at the *product* of problem solving to the importance of viewing problem solving as a *process*.

We utilize a number of interdependent and interactive capacities when we solve problems, as illustrated in Figure 1 below. Thus, it can be argued that problem solving involves a wide range of human abilities and processes. The diagram also shows the interchangeable concepts of problem solving as intelligence and learning, and additionally includes motivation as a driving capacity. Creativity is also included (Wallace *et al.*, 2004).

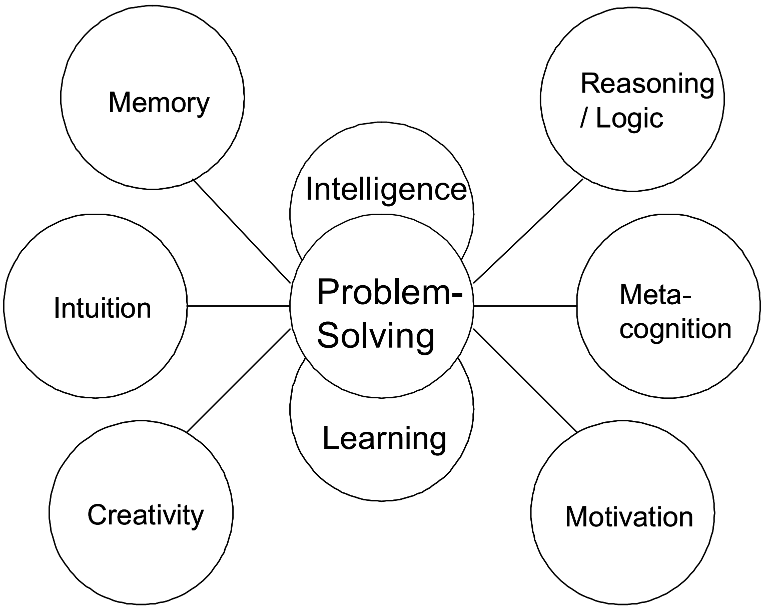

Figure 1: Problem Solving Capacities

Undoubtedly, cognitive science and cognitive learning theories play an important role in our understanding of the mechanism of problem solving and the application of creativity in humans (Newell and Simon, 1972). Studies and experiments carried out by Piaget in the early 1900's show that our ability to solve problems, albeit simple ones, begins to develop as early as two years of age, and become internalized by the time we are 12 years old (Boyle, 1969). Bruner supports Piaget's theories and suggests that any subject can be taught in some honest form (meaning simplified but not incorrect) at any age. He terms this recursive approach to teaching and learning and the development of cognitive skills, such as problem solving, the *spiral curriculum* (Bruner, 1974). Both Piaget's and Bruner's observations of the formative development of problem solving skills and knowledge at an early age present obvious challenges to teaching already developed individuals entering higher education.

In Bloom's taxonomy (Bloom, 1956) the higher level cognitive skills of analysis, synthesis and evaluation are relevant to our ability to effectively solve problems; with the development of these higher level problem solving skills being particularly important in higher education.

But, can we teach or develop students from different disciplines, or even within the same discipline, using the same techniques? The area of psychological types and their effects on a student's ability to learn and the teaching styles employed is not a new area, and has many supporters and critics. Work already exists on the use of psychological type indicators and their relevance to everyday activities, including education.

There are many different indicators in existence, which have recently been critically appraised in terms of their educational value by Coffield (2004). Research undertaken during the late 70's to mid 80's (McCaulley, 1976; Godleski, 1984; Stice, 1987), showed that psychological types have implications for both the learning styles of students and consequently effectiveness of the teaching styles employed. McCaulley links this work on type indicators in its general sense to the implications for teaching engineering students who demonstrate markedly different characteristics from students from other disciplines. Our recent studies confirm these findings (Adams *et al.*, 2007). This work on type indicators is further developed to critical thinking and problem solving abilities by Stice (1987), although not to engineering students in particular. A recent article by Fleming and Baume (2006) revisits learning styles in general through an on-line self assessment process called VARK (Visual, Aural, Read/Write, Kinaesthetic).

Supporters and critics of learning styles alike argue that they should be used with caution in order to avoid the potential of stereotyping students with a particular type, and that type may change with situation and time. They do, however, seem to have the potential for developing self awareness, which is of particular use to this research (Middlewood and Beere, 2005).

In summary, developing problem solving skills in engineering students entering higher education offers a number of challenges. We are often presented with students from a range of backgrounds and cultures, and with a range of different abilities (Woods and Crowe, 1984; Brandt and Sell, 1986). Their levels of motivation for entering engineering may also be different, as are their preferred learning styles and psychological types compared with other students. They have a range of already developed problem solving skills and knowledge which may or may not be entirely correct. Importantly, the problem solving skills to be developed in these students involve higher level cognitive processes whereby the student is expected to think and reflect about the process of problem solving rather than just the product; alongside synthesizing and evaluating a solution.

Teaching Problem Solving

It is argued by many commentators that the emphasis on problem solving in engineering is seen as the product of the problem solving exercise, rather than the process by which the solution or solutions are determined (Stice, 2007). It is also argued that engineering educators tend to focus on teaching content rather than method (Wankat and Oreovicz, 1992).

The teaching of problem solving offers challenges in the areas of strategy and method. It is often debated whether the teaching of problem solving strategy should be integrated into subject modules, taught alongside these modules, or even taught separately. There are a host of different strategies for problem solving, which have been reviewed in detail by Woods (1977). Woods' own method, which is similar to that of Polya (1957) but with one additional step (step 2), considers problem solving as a simple five stage process:

1. Define the problem
2. Think about it
3. Plan
4. Carry out the plan
5. Look back

Teaching process in the classroom can be achieved in a number of ways. One method is Thinking Aloud Pairs Problem Solving (TAPPS), where there is a problem solver and a listener. There are many other techniques, which cannot be explored in this short paper. Another important method for developing problem solving skills in the classroom is the use of Problem Based Learning (PBL) exercises.

In PBL the handling of a problem drives the whole learning of the student (Palmer, 2002; Jackson, 2003; Khan and O'Rourke, 2004). The curriculum is structured as a series of problems as opposed to a systematic presentation of subject content. An extension of this is Enquiry Based Learning (EBL) which, although incorporating elements of PBL also covers a broader spectrum of approaches including small-scale investigations and project work. It must be noted, however, that Problem Based Learning is distinctly different from Problem Solving Learning, with the former being used to develop processes in a wider context rather than products in a confined environment (Savin-Baden, 2000).

It is further acknowledged that while PBL can be used to develop problem solving skills, other interventions are often required to make this effective (Woods, 1991). In order to be effective, students should have some problem solving skills before entering a PBL programme, and PBL offers the opportunity to develop and refine these skills but with some intervention or mediation. Felder (1987) additionally proposes that PBL exercises can also be used to develop creativity.

What is Creativity?

Unlike problem solving, creativity as a concept is rather more complex to define or understand. In a detailed study of creativity, Dewulf and Baillie (1999) explore a number of definitions, finally arriving at a working definition as: "Creativity is shared imagination". In this definition 'imagination' is further defined as novel (rather than visual) memory and individual or personal and 'shared' in a sense of being able to communicate these ideas with others so that they can reconstruct this imagination. It is speculated that we all have the ability to develop our creative potential and that this is influenced by a number of factors such as personality, environment and intrinsic and extrinsic motivation (Abra, 1997). Bohm (2004) observes that creativity is a quality that diminishes from our childhood as our learning takes on a narrower meaning and as we become more afraid of making mistakes or taking risks.

Traditionally excellence in engineering problem solving is usually considered synonymous with skill at convergent production; since engineering education normally involves only problems with a single correct answer. However, this is not particularly true of engineering practice in general.

So, can creativity be taught in the classroom? Felder (1998) proposes that creativity is an ability that we must exercise and augment in our students through a suitable environment and using effective exercises. These exercises should encourage creative thinking by having divergent (multiple) solutions, or potentially no solution at all. He also advocates the use of open-ended questions, where students have to define what they need to solve the problem, and the use of brainstorming and other techniques where students are encouraged to think of as many ways to achieve a specific task. Finke *et al.* (1996) supports this philosophy by concluding: "… the creative problem solver must be able to recognize and avoid habitual or conventional ways of thinking, especially when confronted with novel situations or problems".

Action Research

A review of existing research suggests that deficiencies continue to exist in engineering education in the development of problem solving process skills. Whilst it is recognised that the use of PBL activities may stimulate problem solving skills and creative thinking, research highlights that some form of mediation or intervention is required in order for this to be effective. Further research proposed here intends to investigate the issues involved in developing a range of appropriate graduate skills with undergraduate engineers in order to improve their problem solving capabilities and to stimulate creative thinking. The methodology that has been selected is action research (Carr and Kemmis, 1986) with first year engineering undergraduates in order to develop a problem solving and creativity module. Unlike traditional PBL modules the focus here will be teaching students how to think rather than what to think. It is anticipated to undertake two cycles of action research over two consecutive academic years, although there is scope for a third cycle. Module development will also be informed by interviews with students, academics and professionals in order to establish similarities, differences and opinions of novices and professionals.

The first cycle of action research involving a cohort of 21 first year engineering undergraduates at The University of Northampton ran from the beginning of October 2007 to the end of March 2008 (two academic terms). This consisted of students taking part in 21 weekly one-hour sessions. Participation was on a voluntary basis due to an existing full quota of credit point bearing modules in the first year of the validated course, although this will be reviewed. The module was further supported outside contact time with supplementary material in a Blackboard-based virtual learning environment. Whilst participation in the module was voluntary, there have nevertheless been high levels of engagement ranging from 50% to 100%, but typically 80% in contact sessions. The on-line environment has had over 500 hits. Participants received a small gratuity for taking part, subject to providing feedback, courtesy of a research grant from The Higher Education Academy Engineering Subject Centre.

Content was selected for the sessions appropriate to developing each of the stages of the problem solving process: interpreting the problem, planning, processing, presenting solutions and being reflective. The selection has been informed by previous research. Sessions have been dedicated to analytical and creative techniques such as brainstorming, thinking aloud in pairs and meta plan. Students also undertook a guest-run session on mindfulness training; a meditation technique used to focus the mind. This is currently being researched at The University of Northampton as a technique for top class athletes.

In order to provide an opportunity for students to explore practically the problem solving process, eight sessions (four per term) were dedicated to a series of PBL activities using Lego Mindstorm robots. These sessions drew on established work being undertaken in the development of programming problem solving skills with computing undergraduates (Turner and Hill, 2006; Turner and Hill, 2007). The purpose of the sessions with engineering undergraduates, however, was to provide motivation for developing problem solving skills rather than becoming experts in programming.

Problems presented to students were relatively open-ended thus allowing for divergent or creative solutions. They were also presented in a number of different formats i.e. text, diagram, audio, in order to stimulate different learning styles (i.e. this might be how a professional engineer would be presented with problems in practice). When solving the problems students were expected to use a range of techniques from class sessions, and to present and reflect on the process as part of a team. The problems set were relatively simple and included detecting a wall, tracing shapes on the desk and devising a wall and line following robot. Nevertheless, Lego Mindstorm robots allow the potential for developing more sophisticated or complex problems.

Students were expected to act as co-inquirers in the development of module content and to highlight issues important to them. They were also provided with and encouraged to keep a personal reflective diary as to how they thought their skills were being improved in the context of their problem solving abilities in other engineering subjects.

Feedback from students was in the form of a questionnaire and focus group at the end of each term. Students were also encouraged and demonstrated willingness to provide feedback during sessions.

In addition, 25 semi-structured interviews in total have been carried out with the engineering undergraduates, academics and professional engineers. The purpose of the interviews was to investigate characteristic similarities and differences between expert and novice problem solvers in engineering, and how this might inform module content (Selden and Selden, 1997; Breslow, 2001). The interviews asked three open-ended questions: “what qualities do you think make a good problem solver?”, “what do you understand by ‘creativity’ in relationship to engineering?”, and “how do you think that these skills can be improved in undergraduate engineers?” The interviews are currently being transcribed for analysis, which it is proposed will take the form of a phenomenographic study, the findings of which will be presented shortly (Marton, 1981; Kvale, 1996; Sandberg, 1997; Vincent and Warren, 2001).

Summary of Findings

In one of the early sessions discussing the process of analytical and creative thinking, students undertook a psychological type test to highlight their thinking preferences with respect to learning and problem solving. The psychological type test used was a modified Myers-Briggs (Jung) test relating to learning developed by Pelley (2007). For comparison the test was also completed by students in computing, product design and fine art. Results are shown in Figure 2, and each mark in the table shows a response for an individual student. The interaction of two, three or four type preferences are known as type dynamics, and when dealing with a four-preference combination this is called a type. In total, there are 16 unique types, and many more two or three letter combinations. It is not possible within this paper to provide a detailed interpretation of each type, although many descriptions exist on the Internet. Interestingly the results show engineering students with a tendency to analytical skills of type TJ (Thinking/Judging) and fine art students with creative skills of FP (Feeling/Perceiving). Product design students tend to fall somewhere between the two, while computing students are similar to engineering students apart from showing more introversion. This supports and confirms the earlier work of McCaulley, Godleski and Stice (McCaulley, 1976; Godleski, 1984; Stice, 1987). It must be noted, however, that these findings are a snapshot in time and place, and may not necessarily reflect a students 'type' under different circumstances.

	ES	**EN**	**IN**	**IS**
TJ	XXXXXX +	XXX ++ *	XX +	XXX +++++ %
TP	XX ++ **** %	X ++ * %	+ **	++
FP	X %%	X + %%%%%	X %	
FJ	++ %	** %%%%	%%%	X

X	Engineering		**E**xtravert	**I**ntrovert
+	Computing		**S**ensing	i**N**tuition
*	Product Design		**T**hinking	**F**eeling
%	Fine Art		**J**udging	**P**erceiving

Figure 2: Psychological Types across Faculties

In another session students undertook a learning style preferences test (VARK test) which can be found at www.vark-learn.com. The test shows preferences for one or more of four learning styles: visual, aural, read/write and kinaesthetic. Research suggests that if learning and problem solving are linked then our learning preferences may influence how we interpret, process and communicate with respect to problems. Results of the test shown in Figure 3 indicate the majority of students to be multi-modal with no strong preference for any particular learning style. This result is somewhat predictable according to the tests' author (Fleming, 2001). In subsequent discussions with the students it was discovered that many disliked the use of diagrams; an unexpected observation for engineering students. This phenomenon was also observed in robot exercises where students were unwilling to draw and annotate diagrams in order to help with solving problems presented to them in audio or text format.

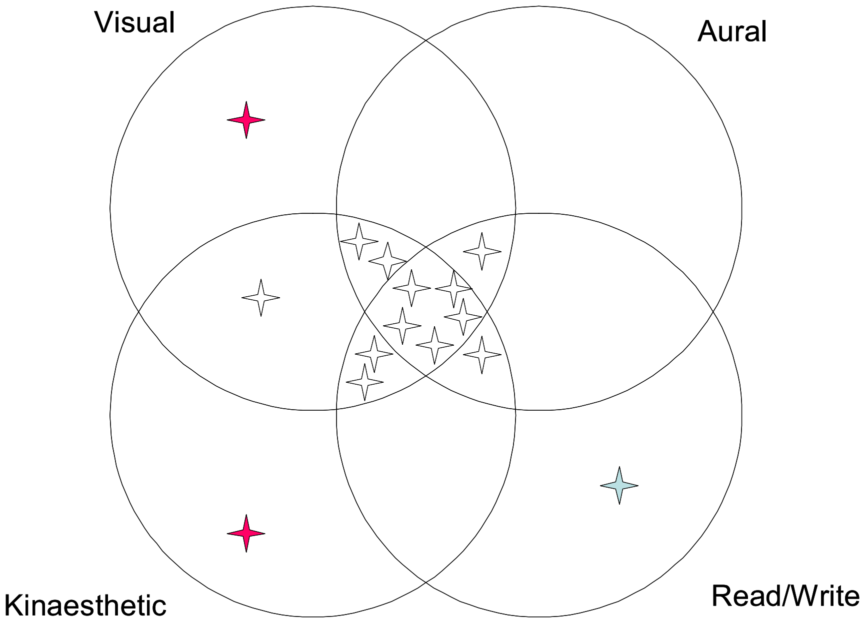

Figure 3: VARK Test Results

In feedback, however, some students were sceptical of the outcome of the above tests and found some of the questions protracted or unrealistic. Other students found the tests useful as a way of finding out about their preferences.

In questionnaires and focus groups students believed that problem solving and creativity were essential skills for engineers, however, in deeper investigation creativity in engineering was seen as something like producing a drawing or making a model. Some associated creative engineering with the aesthetics of product design rather than analytical engineering. One overseas student could not agree at all with engineering requiring creativity or even that intuition had significance in a purely analytical subject. This belief was partially confirmed in interviews with practicing engineers and academics who could not associate with creativity, but saw this as relating to ingenuity or innovation.

Feedback by questionnaire and focus group from 20 students indicated that overall satisfaction with the module was positive (85% rated their enjoyment as high). Students generally believed (50%) that the module had made them better problem solvers while slightly less (36%) thought that it had improved their creative thinking skills. It is appreciated, however, that it is difficult to evaluate the transfer of skills between modules; an area that requires further investigation. The motivation provided by the robot exercises were rated highly, with 78% believing that they were a good method for developing problem solving skills. This was also highlighted in comments where seven students requested the use of robots earlier in the module. When asked if the module would be better as an on-line simulation only 28% responded positively. This is supported by comments about what they most enjoyed in the module including group discussions, groupwork, being able to identify and discuss thinking and problem solving skills and the openness of classroom talks.

In conclusion, whilst feedback was positive with regard to session content, the module tended to be disjointed in trying to develop skills remote from practical activities. It was sometimes difficult to provide, or for students to appreciate, the alignment of transferable problem solving skills discussed in class sessions with practical problem solving activities using the robots. The robot exercises also required programming ability in Java which the engineering students had to acquire. A better approach might be to have a more focused problem task with skills being introduced at appropriate times to mediate the problem solving process. This would suggest an object-orientated approach.

Further work

It is planned to run a second cycle of action research commencing October 2008 informed by the findings of the first cycle and interviews once analysed. In this module the application of robots as a mechanism for developing problem solving and creativity skills will be expanded as a central theme. This is supported by the motivation they have been found to provide in the first cycle. An emerging model is shown in Figure 4.

A number of transferable skill objects will be created to mediate thinking and problem solving in a timelier manner around a core theme. Students will take ownership of this ‘problem space’ by generating and solving a robotics problem. Preliminary evaluation of the interviews indicates issues with students believing that they do not own academic problems set them. The core theme will utilise the latest Lego NXT Robots involving a graphical programming language (based on LabView) that has a much easier learning curve. It will also develop graphical and spatial awareness, which was found to be lacking in the first cycle.

An object-based module may offer the potential for sharing and repurposing of content in which the central theme (robots in this case) may be replaced by something more appropriate to other engineering departments or even other disciplines. In the first instance, objects will be shared for evaluation by computing students.

Interestingly, PBL is described as a ‘component method’ under the umbrella of Instructional (or Learning) Design (Reigeluth, 1983); one of the main educational philosophies behind the use of reusable learning objects (Wiley, 2001; Koper, 2006). Whilst reusable learning objects are generally employed as ‘content chunks’, learning theorists are pushing for their use in case-based problem solving scenarios. When learning is in the context of problem solving then reusable learning objects change from info-capsules into semiotic tools to mediate and shape the learners’ actions (Wiley, 2004). The ‘tool’ aspect of learning objects in their mediation of problem solving in PBL contexts remains an area which is almost completely unexplored, and therefore offers potential to this research.

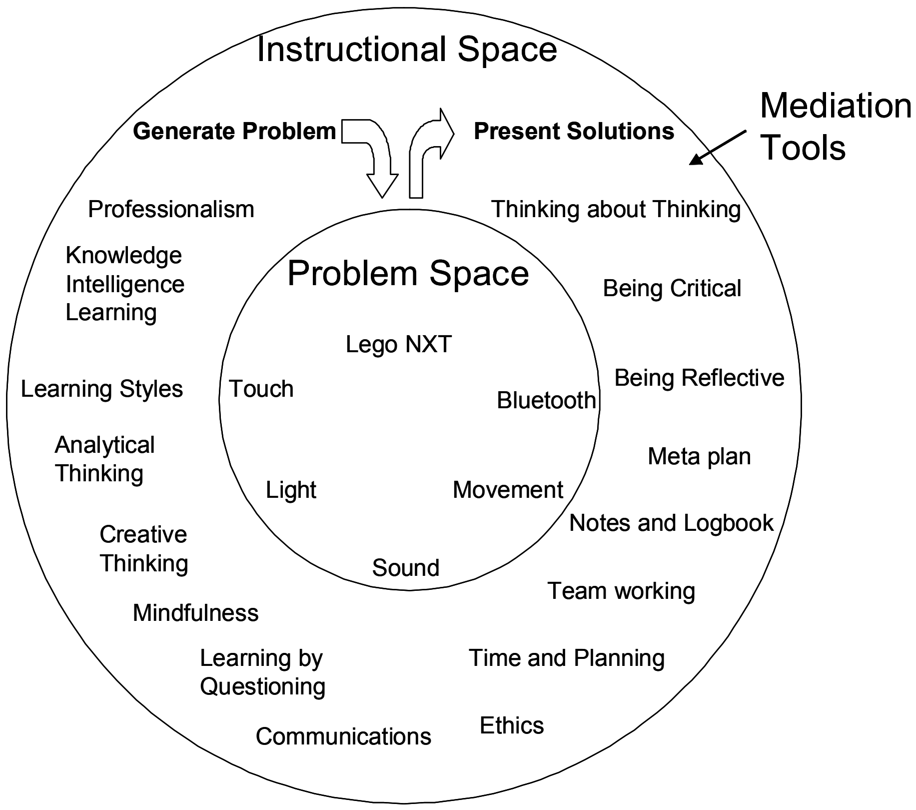

Figure 4: Developmental Instructional Design PBL Model

Conclusion

It is evident that the ability to solve problems is an essential attribute for an engineer, and one that should be developed, by whatever means, to the full potential in engineering undergraduates. Whilst it is difficult to qualify if it is even possible to teach or measure creative potential, it is certainly a quality that should be encouraged in engineering undergraduates through the use of a suitable classroom environment, exercises, self reflection and awareness.

The use of suitable Problem Based Learning exercises involving robots offer the potential to explore the process of problem solving in a fun and risk free way without the burden of requiring extensive knowledge. With suitably devised exercises they also allow for creative thinking.

In order to be effective, however, the development of thinking and problem solving skills through Problem Based Learning activities requires mediation and timing. Without this intervention then this might be a lost opportunity.

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