Problem Solving and Creativity in Engineering: Perceptions of Novices and Professionals

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***Abstract*— Current UK and European benchmark statements for both undergraduate and professional engineers identify problem solving and creativity as essential capacities. They do not, however, offer guidance on how these skills might be fostered or assessed.**

Researchers have for many years explored how the differences between novices and experts might show educators' techniques and strategies for improving problem solving skills in their students. They also suggest a number of capacities relating to creativity which might vary from professionals to novices.

A number of semi-structured interviews have been undertaken with engineering undergraduates at The University of Northampton, Loughborough University and Birmingham University in order to explore these issues. The interviews with novice undergraduates are further supported by interviews with practicing professional engineers and engineering academics. Analysis has been in the form of a phenomenographic study.

Early findings from the interviews have usefully been used to inform an action research project to develop a problem-based learning module to improve creative problem solving skills in undergraduate engineers. A number of emerging themes that have been identified include: confusion with the concept of 'creativity' in engineering; identification of processes in the case of professionals against products in the case of students; issues with motivation and ownership with regard to academic problems and significance being placed on real life activities as a way of teaching and learning creative problem solving.

***Index Terms*— Creativity, Problem Solving, Professional, Novice, Phenomenography**

I. INTRODUCTION

An ability to solve problems creatively is highlighted as essential characteristics for both novice undergraduate engineers and qualified engineering professionals in UK benchmark statements [1, 2]. Creativity within the sciences, including engineering, is also identified, both explicitly and implicitly as an important driver in recent UK reviews relating to economic prosperity and Government science and innovation policies [3, 4]. In Europe, problem solving and creativity are presented as important competencies in the requirements for European Engineer (Eur. Ing.) designation [5]. None of these benchmark statements or policies offers any guidance on how these skills might be fostered or assessed.

Strategies for teaching problem solving and for the development of creativity can be found in many texts, and in numerous research publications [6-9]. It is possible to identify, from both anecdotal sources and more defined evidence that deficiencies continue to exist in the teaching of creative problem solving skills, and that the traditional model of teaching used in engineering education may not provide sufficient motivation for engineering undergraduates [8]. Valuable research also exists on the characteristic differences between expert and novice problem solvers, and how this can help our understanding of developing problem solving skills in the classroom [10, 11].

In order to investigate current perceptions of novice and professional engineers, fifty semi-structured interviews have been conducted over a two year period as an extension to an action research project involving engineering undergraduates at The University of Northampton [12, 13]. The interviews with novice undergraduates are further supported by interviews with practicing professional engineers and engineering academics. The interviews have been conducted at The University of Northampton, Loughborough University and Birmingham University.

This paper provides a brief summary of previous research into the differences between novice and expert problem solvers, and characteristics for creativity, alongside findings from an initial twenty-five interviews undertaken with professional engineers and students and academics at The University of Northampton. Work is currently underway to provide a comprehensive analysis of all fifty interviews. The interviews extend their questioning and comparison beyond problem solving skills into creative thinking.

II. EXPERTS AND NOVICES

There are reportedly a number of characteristics that differentiate an expert from a novice problem solver. These include the use of memory, attitude, strategy and visualisation [14]. Perhaps central to this difference is how experts and novices initially think about problems. Experts

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tend to examine the problem as a whole before moving to a physical representation of it. Only then do they employ formulae and equations to solve it. Novices have a tendency to jump straight in [10].

Defining the terms “problem” and “expert” offers us more challenges. A problem could be a routine text book exercise or a complex mathematical task. Similarly, an expert may be someone who knows the domain thoroughly and can solve problems in an automatic manner, or someone who can abstract process skills and utilise these in solving non-routine problems. Whilst experts often possess extensive knowledge, it is the latter that are more successful in solving unfamiliar problems.

Studies carried out by cognitive psychologists such as Larkin and Simon et. al. [15-18] in the 1980s often employed text book exercises that physics novices and experts had to solve. Their studies observed and identified behaviour whilst solving the problems, and made suggestions for improvements in instruction. Typical findings were that experts tended to “work forwards” looking at the givens of the problem first and moving from the problem statement to a physical representation of it. Only after this analysis did they apply equations and formulae. Novices were observed to employ a “working backwards” approach trying to find what procedure would get them to the answer. They tended to adopt a more ‘trial and error’ approach; memorising and applying equations independent of context or relationship to the problem.

Similar studies with engineering students confirm these earlier findings with physics students [19, 20]. Students who were successful were able to apply specific pieces of knowledge in order to solve problems. Unsuccessful students were unable to relate what they had learnt to problems that were of a non-familiar nature.

These studies were performed at a micro level; observing process whilst solving often well-defined problems of a mathematical nature. They nevertheless highlight and reinforce the importance of teaching and developing process skills involved with problem solving, such as those in Pounds’ [21] eight-step model (select a problem, consider alternative solutions, evaluate solutions, select a solution, execute solution, chose a model or goal, compare it with reality, identify differences) or Woods’ [9] five-step model: (define the problem, think about it, plan, carry out the plan, look back).

Unlike problem solving, creativity as a concept is rather more difficult to define or understand. Research relating to creativity appears not so well defined in terms of identifying characteristic differences between novices and experts. Dewulf and Baillie [7] identify through a detailed literature review and by way of several case studies in arts, science and engineering a number of attributes required to implement creativity. Some of these attributes might be considered to differentiate novices from experts including: knowledge [22], intelligence [23], motivation/enthusiasm [24], memory [25], environment [24] and communication [26]. Other attributes identified are thinking skills (convergent and divergent), creative techniques, personal and group work, freedom to experiment and reflection.

It might also be speculated that we all have the ability to demonstrate and enhance our creative potential [24]. Bohm [26] observes, however, that creativity is a quantity 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.

In order to confirm and investigate issues identified in previous studies, and to further explore the concept of creativity in engineering the approach adopted in this study is at macro level; seeking perceptions and views of novices and experts through a series of interviews rather than by analysis of creative problem solving in practice.

III. Interview Process and Analysis

Fifty semi-structured interviews in total have been carried out with engineering undergraduates, academics and professional engineers although this paper only considers an initial twenty-five. 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 the development of problem solving skills and creative thinking in a dedicated problem-based learning (PBL) module with undergraduate engineers. 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 have been digitally recorded, and transcribed. Overall length of audio data for all interviews is approximately 30 hours, and 15 hours for the initial twenty-five interviews considered here. Whilst detailed analysis is still in progress, this is in the form of a phenomenographic study [27-30].

Phenomenography is a research technique developed by Ference Marton in the late 1980’s [27, 31] that can be used to investigate the qualitative differences of how people think or perceive something. Phenomenographic data is collected through a series of open-ended interviews, which are then transcribed and analysed through iterative readings to produce an ‘outcome space’ [32]. The ‘outcome space’ represents an ordered set of related categories of the concept being studied.

The method through which the interviews are obtained, and transcripts produced are of particular importance to the research process in order to avoid bias, misinterpretation or loss of data [30]. Interpretative awareness relies on a technique termed ‘bracketing’ whereby the researcher brackets or suppresses their own preconceived ideas whilst performing interviews, or analysing transcripts [28, 33].

The results presented here represent an analysis of the initial twenty-five interviews and transcripts, alongside a selection of direct quotations. Early indication is that the remainder of interviews undertaken at other universities tends to support these initial findings.

TABLE I. SUMMARY FOR QUESTION 1

Student	**Academic**	**Professional**
Analysis of question	Experience and Practice	Naturally enquiring mind
Practice	Trial and Error	Motivation to make things better
Analytical skills	Prior knowledge	Asking questions and asking others
Variability in terms of ownership	Reflection	Scoping of problems
Motivation: grades, learning, career	Sorting information; synthesis	Recognizing what you do and don't know
Maths skills	Good understanding of what to be achieved	Flexibility in method
English skills	Skills and not content or knowledge	Reflection on method and having other strategies
Consulting with others		Thinking in different ways (pictures)
Looking from other viewpoints		Questioning and listening
Communication		Making things basic/simple
Priorities and Focus		Thinking skills
		Logic skills/process skills
		Analysis and application of analysis
		Risk taking

TABLE II. SUMMARY FOR QUESTION 2

Student	**Academic**	**Professional**
Natural thing	Product design – you mean ingenuity	Making things better
Visual, product design, musician, artist	Relates to manufacture, architecture, design	Innovation
"Think out of box" "Step out of box"	Easier to see in artist or musician	You are or are not creative
Knowledge	Problems with word "creative"	Born with it, but can be improved
Intuition	Design flair and knowledge	Questioning
Links to logic	Merging of disciplines	Doing something that a computer can't do
Objective not subjective in engineering (it has to work)	Techniques like brainstorming	Solution that is not out of a book
Direction without being given	People who work outside in	Close to devious (in terms of patents)
Something new	Producing many solutions against criteria	Moving away from the norm
Different perspectives	Relates to logic	Requires correct environment
Brilliant ideas	Challenged to think	Increases under pressure
Not black and white		

TABLE III. SUMMARY FOR QUESTION 3

Student	Academic	Professional
Practical work	Reflective tasks	Communication skills
Group work	More practice	Practical work within abilities
Technical work	Practical work, but simple	Developing questioning
Business skills (presentation and reports)	Communication skills	Thinking and questioning skills
Clear links between theory and practice	Group discussion of problems	Thought processes
Competitive tasks	Problems with multiple solutions	Adding of process skills to assignments - reflection
Free time for exploration and research	Mini projects	Developing process skills
Interaction	Constraints to take out of usual methods (adaptation of problems)	Giving surprises or adaptations
Profiling of students / differential teaching	Placing values on skills developed	Being challenging, ambitious problems
	Explain benefits to them / articulation of skills being developed	Techniques (e.g. brainstorming, logical approach etc.)
		Group decision work / Teamwork
		Real world problems / motivational
		Environment to develop and hone skills
		Study groups
		Case studies and briefs

IV. FINDINGS AND ANALYSIS

Tabulated results presented here relate to the three interview questions asked and are grouped into related response categories from students, academics and professionals. Some ordering of importance is present within each of the category lists in order to form an 'outcome space' of responses. Direct quotations are identified with S, A or P denoting student, academic or professional respectively. A more detailed analysis of transcripts and recordings is currently being undertaken.

Q1: What qualities do you think make a good engineering problem solver?

An analysis of responses to Question 1 is shown in Table I. These indicate a continuum from students to professionals on the importance placed on process skills such as thinking and reflection. They also tend to suggest an increased importance placed on method and strategy by professionals.

P: "Flexibility in method is important; if plan A doesn't work then diagnose your approach; you need the ability to step back and see objectively what you are doing."

A: "Students don't reflect the way I see it; people tend to concentrate on teaching content rather than key skills."

Whilst students were able to identify a range of important skills these were often presented in a rather disconnected way. Academics identified a range of issues but like students tended to focus on the understanding of the question and learning by practicing rather than the importance of identifying and developing method.

Motivation also varies across this continuum with students being motivated by more immediate and tangible commodities such as grades and employment opportunities. Professionals tended to take a different view of motivation, relating this to having an enquiring mind and the desire to explore engineering issues more liberally.

S: "Motivation is wanting to learn and end grade."

A: "Motivation is a two way thing; you need to challenge and motivate students."

P: "Motivation is important into making things better than they already are."

Interestingly, students also indicated issues with ownership of academic problems set them, with over 50% believing that ownership was either shared with or belonged to the person setting the problem.

S: "I don't own the problem as I have not dreamt it up."

S: "Ownership of the academic problem is clearly with the problem setter."

Q2: What do you understand by 'creativity' in relationship to engineering?

Analysis of responses to Question 2 is shown in Table II. These suggest that confusion exists with the understanding of the word 'creativity' with many respondents associating this with artistic or design activities. Alternatives like 'ingenuity' and 'innovation' were seen by some as more appropriate to engineering.

S: "Creativity is quite tough to define as an engineer; is it design problems?"

A: "It's what the product designers do, you're getting it confused with ingenuity; creativity will sell a product, but ingenuity will find a new way of manufacturing it."

P: "A solution that is not blindingly obvious to someone with similar skills and experience; I think I have given you a definition of innovation; the novel step."

There seemed also to be some general agreement that creativity in engineering means devising a process or solution that does not follow conventional methods.

S: "Creativity is thinking of something new."

A: "I suppose it is a mixture of design flair and engineering knowledge; creativity is the merging of several disciplines; form, fabric and function all merges."

P: "Creativity is part of making things better still; if you have not got a creative outlook then you are doing something by hand that a computer can do."

Many respondents also believed that creativity, like having musical ability, was something that was internalized although it was also speculated that it could be improved or enhanced.

Interestingly, several professional engineers saw creativity in a commercial context as being related to being 'devious' in order to avoid legal issues with product patents.

Again, varied responses exist as to whether creativity involves the creative potential of the individual, creativity in the process or creativity of the artifact.

Q3: How do you think that these skills can be improved in undergraduate engineers?

Analysis of responses to Question 3 is shown in Table III. All groups of respondents highlighted the development of problem solving skills and creative thinking through practical activities and exercises as being important.

S: "Let us try more practical things; solving of equations is just maths, you need to relate this to practical things."

A: "They don't have hands-on experience; they have not built things and failed."

P: "Give student's real problem to solve not just routine calcs; put them in an environment where they can demonstrate skills and hone the skills that they already have."

Communications skills and group and team work are also identified by each group as another important element.

S: "Group work brings out skills in individuals in others that they cannot express when working individually."

A: "Communication is useful for a whole range of jobs; students need to see value in the skills that are not being tested."

P: "Spelling and communication skills- presentation is all; in industry there is not always a next time."

Again, analysis shows a continuum in terms of the importance placed on the development of process and thinking skills, with professional engineers identifying and rating these abilities more highly than engineering students. The setting of realistic problems which introduce challenge, surprises or adaptations are also highlighted by professionals as being useful.

S: "There needs to be incentives to do things that are not part of the core."

A: "Students need to be far more switched on; they need to reflect and question things."

P: "I don't want yes people, they must be able to think and question. They must be able to handle surprises and more than one thing at a time; at the end of the day you need to be ambitious."

V. Conclusions and Further Work

Analysis of the first twenty-five interviews and transcripts highlights a number of interesting themes which tend to agree with the findings of previous studies. A number of additional issues are, however, also identified. The research techniques used in this work are different from previous studies which use observation of solving mathematical problems as opposed to open-ended interviews.

Responses to Questions 1 and 3 demonstrate a continuum between identifying skills in the case of students with that of identifying both skills and problem-solving process in the case of professionals. Students tended to be focused on analysing the problem and identifying skills (which they might already have) to assist with working a solution (working backwards). Professional engineers on the other hand take a broader outlook by considering the task as a whole while selecting and adapting strategies which include both skills and method (working forwards). Interesting observations were also made regarding motivation and ownership, with both having a more reward-biased focus for students compared with the more liberal attitude of engineering professionals. Reflection, problem visualization and communication skills are also highlighted as important attributes by both professional engineers and academic. All three groups of respondents identified practical activities including case-based scenarios and 'real world' problems as a good way of teaching and learning creative problem solving.

Creativity (Question 2) was seen by all groups to be a difficult concept to define. Many had difficulties with the word 'creativity' in an engineering context, preferring to use other terms such as 'innovation' or 'ingenuity'. It was also often perceived that creativity was a skill that you were born with; an innate ability. Whilst most respondents agreed that there was scope within engineering for creativity, many could not give a clear definition of what this meant in practice. Respondents tended to agree that their understanding of creativity within engineering was to do with moving away from conventional solutions, or as many quoted "thinking out of the box"; the focus here being on the end product and only partly on the process. There was a general lack of awareness or agreement by all respondents in terms of creativity involving the creative potential of the individual, creativity in the process and creativity of the artifact.

Work continues with the analysis of interviews and transcripts in order to provide a more detailed study. A number of further interviews have already been conducted at Loughborough University and Birmingham University, and the interviewing process is now complete. Due to the amount and richness of the data, clustered concept analysis is being undertaken in the qualitative research software Nvivo [34].

Early results from this research have already been used to inform the development and content of a dedicated problem solving and creative thinking problem-based learning (PBL) module for undergraduate engineers.

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