Fostering Creative Thinking in Student Engineers

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SUMMARY *In order to prepare engineering students for a changing future and to help them develop their own capacity for independent innovative thought and creative problem-solving, we are faced with the need to explore ways of fostering creativity in students within engineering programmes. We see the need to focus on how to access creativity, how to develop an environment which is less constrained and which will allow creative flow. Three case studies are presented which demonstrate the importance of establishing the freedom of the learning process as well as providing motivation, whether extrinsic, in terms of the assessment scheme, or intrinsic. This latter might take the form of helping students to realize that the process of learning is a process of invention in itself and that students need to recognize their existing creativity and capacity for engagement. The very important and yet elusive issue of evaluation is also considered for each course. We discuss how to monitor the level of success in achieving the given objective of fostering creativity in students.*

1. Introduction

Engineering and technology have not always had the plain, functional flavour that we associate with them today. Engineers have been known to celebrate their achievements with an artistic flair, sometimes with ornate flourishes, yet others with intriguing simplicity. Engineering of the distant past was perhaps more an art than being married to science, as we think of it today. Engineering builds things up, often as unique creations which can herald their existence as works of technology and statements of art. There are many and increasing pressures facing engineers and engineering education today—from funding bodies, professional institutions, government bodies and industry, who are suggesting that engineers need to develop wider and more responsive skills and approaches to engineering in its social context, in fact to revisit that ability to discover creative solutions to engineering problems.

The Institution of Engineers, Australia [1], in a recent review of engineering education, proposed the need for "a high level of understanding of the broad human, economic and environmental consequences of the professional tasks engineers have to face today". There is a strong push from the environmental engineering and women in engineering programmes towards a 'culture change' before this broadening can happen, in which students must develop 'innovation and creativity' [2], and the development of 'creative imagination' [3]. Creative solutions are needed by companies in order to diversify and respond to market challenges. Companies such as the BOC group employ innovators whose sole task is to find creative applications or new areas of diversification [4]. Research supported by the Council for Industry and the Department for Education and Employment, UK [5], suggests that employers want more than adaptive recruits,

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they want "employees who can use their abilities and skills to evolve the organization". They are looking for "people who can use higher-level skills, such as analysis, critique, synthesis and multi-layered communication to facilitate innovative teamwork: transformative employees". In order to address these issues the *SARTOR* (standards and routes to chartered engineer status) document [6] prepared by the Engineering Council, UK, states that to obtain full accreditation for chartered engineer status and Meng courses, universities would be required to show how graduates could achieve "the ability to be creative and innovative". It is now up to the educational institutions to discover ways of fostering creativity in students.

Various programmes have been initiated worldwide, particularly in the first year, with a focus on facilitating students' independent learning skills, motivation, responsibility as well as endeavouring to develop skills and attitudes towards a professional career. Mostly, these have been introduced via an introductory course or an entire curriculum reform [7]. In order to solve professional problems, students will need to develop more open-ended problem-solving skills, where there is not one set solution. This requires more imagination, innovation and creativity. In this paper, we will be looking at three programmes which have been implemented which aim to foster creative thinking in an engineering-related context.

2. What Is Creativity?

It would be appropriate to ask at the outset: What is creativity? What is the nature of the beast? Often, it appears to be a faculty, an ability, something inside people that enables them to do things considered to be creative, or more simply, to create. There appears to be a great deal of similarity between the way we collectively regard creativity and other characteristics of performance, such as intelligence, or aptitude, or ability. Such notions may provide a ready and facile explanatory principle, but one can go no further; there is no access to creativity, no opportunity to cultivate it as a skill in oneself or others.

In systematically fostering creativity, we face a fundamental dilemma: creativity is a convenient label for what is a quintessentially subjective phenomenon. Creativity does not occur as such for the person in the act of creating; it is a descriptive term applied after the fact, or by an external observer. Yet we seem, by necessity or perhaps merely tradition, to be confined to these 'objectified' descriptions of phenomena, which really give no access to someone trying to learn to be creative. The methods of 'teaching' creativity discussed below are therefore necessarily different from teaching engineering knowledge, for example. They are facilitative rather than authoritative, and their outcomes are inherently more difficult to measure. We need to address these essentially subjective phenomena using a different approach, if we are to obtain any meaningful access to it. In evaluating our programmes and in assessing student outcomes where appropriate, we have focused on how students think about an assignment task in a creative way and how they express their thoughts on paper. It would be useful to extend our line of questioning started a little earlier, and ask: What is it to create? and again consider the common conceptions concerning what one might do with one's creativity.

3. Developing Creativity Within Constraints

A recent paper on creative problem-solving for engineers [8] focused on the need to remove the constraints of previous knowledge and assumptions before students might start to think creatively. The three case studies to be discussed below are examples of programmes which have been developed in order to motivate students and foster creativity by removing some of the usual constraints from the learning experience. However, we quickly discover, as soon as we try to remove constraints on the students learning and assessment, how many constraints we are under ourselves. We need, therefore, to be able to remove ourselves from assumptions and think creatively about how we might work within imposed constraints. Few of us are in the lucky position of having the time and the freedom to create new courses and implement them just as we wish. We are battling with time constraints exacerbated by quality assessment exercises, which insist that our research becomes the focus of our attention, as well as increasing administrative demands. We are facing larger classes owing to higher student numbers. Further, the institution will often adhere to tight quality assurance mechanisms which make innovations difficult and lengthy beaurocratic procedures for implementing any changes to the curriculum which are offputting and prevent departments from being enthusiastic about any proposed alterations. Suggestions for effective implementation have been collected in a recent survey [7] and made by academics at institutions in 12 different countries, which have been involved in implementing innovations to the engineering curriculum. As it will rarely be possible to create such a positive environment for change, it is worth considering where the support will come from once you face the resistance. If this is not provided in some way, it is likely that any new programme will fail. Educational development teams or other institutions trying similar programmes may be possible sources of advice at this point.

4. Three Case Studies: Fostering Creative Thinking

The three case studies we shall now consider focus on developing an environment which allows for the freedom we have discussed, to allow for creativity and then the motivation required to generate autonomy in students. The first two case studies demonstrate extrinsic motivation via assessment and show how assessment needs to be set up to drive the learning process. They are also used to try to demonstrate again how important it is to realize the constraints within which the programme is being implemented and to work effectively within these. The third example shows how intrinsic motivation may be the driving force.

5. Starting with the First Year: Creating a Base for Better Learning in an Engineering Degree [9, 10]

5.1 The Programme

A first year course, Professional Engineering, was created in the Mechanical Engineering degree programme of Sydney University in order to enhance the thinking skills of the engineering student—develop the students' ability to think for themselves and both to find (ask questions about) and to solve (discover answers to) the problems facing today's society. In order to achieve this aim, the team decided to divide the class into three smaller groups so that each lecturer could take one group at a time and rotate as team teachers. Specific issues were addressed by incorporating within the course a teaching approach and range of activities which allowed small groupwork, discussions, debates, role plays, competitions, interviews, presentations, communication exercises, learning how to learn sessions, industrial visits, etc. Additionally, the emphasis of the course was directed towards the responsibility of the student as a learner and as a future engineer. Hence, ethics, liability, environmental issues and occupational health and safety were considered in context. It was possible to incorporate a wider value set as the three lecturers came from very different backgrounds.

5.2 Assessment and Evaluation

A very important part of the course was the assessment, which was a report-writing exercise. A written report is often the formal vehicle for professional decision-making. As well as conveying the conclusions of the study its purpose is to publish the thinking process of the professional so that this process can be exposed to critical assessment. In writing a report, the professional recognizes that certain levels of quality are required. The students are asked to select one or more topics from the course and are asked to feel free to use their imagination. They then submit a paragraph as a proposal of what they would like to convey in the report. The paragraphs are reviewed and comments fed back to the students with the go-ahead, or they are asked to resubmit. In writing the report students are encouraged to be as opinionated as they like so long as there is evidence to back up their claims. They are permitted to use any information available to them—libraries, computer networks, newspapers, interviews with industrial representatives, surveys, etc. Students are particularly encouraged to choose a topic of interest to them.

The course was evaluated to investigate whether it was in fact meeting the desired aims. Three methods of student evaluation were selected, thus ensuring an element of triangulation—questionnaires, interviews and discussion groups. Informal feedback was given from the lecturers about their perception of how students received the course and how effective it was. It is really only possible to glean information about the creative thinking process of students in an open-ended way. Reflective statements allow us to explore the way a student is thinking about their learning, so long as we ask the right questions. Typical comments which helped us to see that we had provided the required space necessary for creativity were as follows:

> We do discuss topics that are applicable to us in future and you know we spill out even bizarre ideas on how to solve problems which are environmental problems, crazy ideas that I think might be stupid now but might work.

Analysis of student outcomes can give us information about the success of the course in achieving our aims. There are dangers associated with using assessment as an evaluation tool for the following reasons: the assessment may not be an effective measure of all aspects we need to evaluate; it is not possible to compare one student cohort with the next as a measure of improvement; the skills taught and assessed in the new scheme may not be the same as those in the previous system, so we are not comparing like with like. The nature of their reports could be analyzed in this example as we set up the assessment to allow for freedom of thought. Evaluation of student outcomes was carried out using the SOLO (structure of the observed learning outcome) taxonomy of Biggs and Collis [11], which allows us to look for a hierarchy of levels of ways of expressing learning from pre-structural (no relevant information), unistructural (one relevant aspect focused on) multi-structural (several aspects focused on in isolation), relational (several factors considered and related to each other) and extended abstract (learning transcends the given topic). It was possible to look at student work to see if imaginative reports had in fact been produced. The work was of an extremely high standard for first-year students. All of the reports seemed to be in the higher categories of taxonomy. Students showed that they were thinking about the various aspects of the course and were able to relate them together, and many showed originality in their ways of expressing ideas as well as in their choice of projects. It seems that the flexibility of our requirements for the report was necessary to allow students to be more creative.

6. Case 2: The Power Test: Its Impact on Student Learning in a Materials Science Course for Engineering Students [12]

6.1 The Programme

The materials course in focus here is a core course for students of mechanical, mechatronic and aeronautical engineering programmes. The course had traditionally been one of many lectures covering a large factual base and with a final unseen closed book exam. In the first year of change, students were taught using more interactive techniques in a small group setting, in order to help them think more creatively about real materials issues. The exam, however, followed the traditional format, closed book, timed test with mostly well-defined descriptive questions or calculations.

Students expected that the exam would take the same format as in previous years and planned their study with this in mind. Results were somewhat disappointing—while most students could reproduce varying amounts of relevant information there was little evidence that any deeper learning had taken place or that students were able to integrate the facts that they had acquired and relate these to engineering. In discussions with students, it became clear that, however interesting they had found the course, the intentions were being undermined by the assessment, in particular the final exam. With fixed expectations of assessment, many students made it clear that, however interesting they might find class experiences, their learning would be focused on memorizing facts for the final exam. It was apparent that the exam would need to be rethought before students would consider different approaches to their learning.

It is worth pointing out at this stage that attempts have also been made on other courses to implement a new assessment style question—more open-ended, into an otherwise traditional closed book, fixed time framework—and this has proved worse than useless. Students find it hard to swap between question styles and, despite practice, do not seem to be able to 'create' within such a strict framework.

6.2 Assessment and Evaluation

It was decided in this instance to change completely the assessment strategy. An open book exam was chosen due the perceived closeness to what a graduate engineer might have to do on the job. It has been found [13] that open book exams develop deeper study of course material and can help to develop important professional skills. However, there are often problems associated with students taking too many books into the exam room, copying of lecture notes can happen, exam anxiety is still present and time constraints are worse as students need time to look up facts in books.

The solution was to use a 'power test' [14]—an untimed examination which allows students to attempt challenging problems by reducing unrealistic time constraints. It can be conducted as an unseen exam under exam conditions if required. As Rowntree points out [15], it is possible to reduce the time constraints without "letting everything else go", and students can be in an examination room with an unseen paper but be allowed to take all day over it if they wish. Rowntree suggested a further refinement, allowing students to confer with colleagues just as professionals would do.

Hence, the power test was introduced with carefully selected questions designed to match objectives, the number of textbooks was limited and students could take up to 1 day (this was reduced to 4 hours in the second year, as some students felt they had to stay the duration). They were to be in the examination room and could not confer while writing the test, but would be able to leave the room at set times to visit the library, confer with colleagues or have a break. Students were not allowed to take anything in or out of the room while they were taking the exam.

The evaluation of this course took the form of nominal group technique discussions and interviews. Students in the group discussions agreed that there was now more room for independence in choosing what information to use and how to answer the exam questions. In interviews students told us:

> Normal exams test how much you have stored in your brain—but they are not testing your thinking abilities—in a normal exam which is not open book—you are not testing thinking but your memory.

> The exam tested two things—your understanding and your ability to explain what you understand, i.e. how all those little steps connect together in your brain ... understanding for some things can be a step-by-step process and in other ways it will bring two topics together ... to make another idea. The step-by-step process includes both lateral and logical thinking ...

> Open book is a lot harder because you have to research the question—the exam has to make you think, otherwise everyone would get every answer right—the whole way you answer an open book exam has to be different because its not testing your knowledge of the data but how to come to a solution.

The exam questions on this paper were also assessed using a SOLO framework as above. It was found that in previous years the style of question had not allowed for higher level answers (relational or extended abstract). Although at first glance some descriptive questions can appear to involve thought, if the student is able to remember verbatim that part of the notes referring to this topic then they do not have to think, but regurgitate. A question needs some element of open endedness if it is to inspire any creative thought. There cannot be one right answer. It is the ability to formulate a reasonable response by demonstrating the thinking process and to go to the right sources of information that we desire as student learning outcome. For the power test criterion we referenced using the SOLO taxonomy, responses ranged from multi-structural as a pass to extended abstract for high distinction. Very few failed the course and students were able to demonstrate the way they were integrating their understanding of the material and applying it to engineering contexts in imaginative ways.

7. Case 3: A Physics Seminar [16]

7.1 The Programme

If creativity and innovation were thought of as resulting from skills to be developed distinctly in an undergraduate programme, it is likely that such attempts at skills development will compete for time with traditional content delivery in the curriculum. In well-established universities, this will almost inevitably be an intrusion that is vigorously resisted, with limited endorsement by the academic community at the level of individual teaching departments. The seminar programme presented in the physics department sought to make this a non-issue by promoting a perception of creativity as inherently operative in the process of learning, even in the most abstract and traditionally defined academic content.

The seminar programme develops an appreciation of epistemological issues by a quasi-Socratic dialogue, with the teacher acting as facilitator, stimulating an inquiry into conceptions of learning (and teaching), based as directly as possible on the students' experience of learning. This approach is preferred because other methods are considered likely to be subverted by the current epistemological paradigm that students are operating within. If at least some of the students are less than effective learners, a teacher-centred lecture or seminar on the topic of learning is likely to be received in much the same way as all other lectures or seminars—*in extremis* as a package of abstract information of unclear relevance to be recorded and perhaps given some thought, but not really to be engaged with. A provocative style of interaction assists in challenging students to think freshly about the assumptions that underlie their learning approaches and behaviour.

For example, the group of students attending the seminar is asked to identify what they find difficult about learning physics, and the individual answers to this are recorded on the board as a list. When the list is looked at as a whole, a pattern emerges which points to the underlying conceptions of learning. Other studies [17] have shown that the learning conceptions of the majority of first-year physics students are concentrated in surface learning categories, and it is this picture that emerges in the interpretation of the lists generated in the seminar. That the students attending begin to see this for themselves is a crucial step in the process that the seminar aims to guide the students through. The ultimate intention of the process is to enable the students to take a new view of the educational structures that they are currently operating within and to be able to take optimum advantage of what they have available now, as indeed some of their peers demonstrably can.

While teaching practices and curricula could no doubt be improved, this is a long-term process. It is suggested that students could obtain much greater value from existing structures than, on the whole, they currently do. While students and teachers alike tend to explain away difference in performance as being due to variations in ability or application, this programme subjects that assumption to question and proposes that ability is much more malleable than generally presumed. The seminar focuses on the intrinsic motivation towards learning and seeks to undermine the almost conspiratorial resistance of the student culture to engaging with the learning process in any deep sense.

The major thrust of the seminar programme is to develop an appreciation among students themselves, that learning is an inherently creative process, even in circumstances where the material to be learnt appears to be *a priori* well defined. This is consistent with much recent research into conceptions of learning and teaching in higher education [18]. In the seminar, the paradigm within which learning is regarded as the intake, retention or assimilation, and subsequent reproduction, of external information is subjected to incisive questioning and comparison with experience, using both reflection upon actual learning experiences and allegorical visual perception exercises. To the degree that the prevailing conception can be found wanting, it is possible to suggest a deeper conception of learning—expressed in the form "the process of learning is a process of invention". The implications of this position for fostering creativity are far-reaching. It may not be necessary so much to develop creativity *ab initio* as to have students recognize their existing creativity and capacity for engagement. Even relatively casual observation of students behaviour might substantiate a view that it is not a matter of students being creative or not, but a matter of what they are creative about. Much creativity and ingenuity may be evident in extra-curricular areas where students see the clear relevance and worth of intensive engagement in particular undertakings. If they were able to see the relevance and worth of similar kinds of personal engagement in academic learning, as would be the almost inevitable consequence of a genuinely enlarged conception of the nature of learning, the approaches to learning are far more likely to develop towards more creative and effective styles.

7.2 Evaluation

The seminar programme has been evaluated via student questionnaires and interviews of several students. The questionnaires, filled in immediately after the seminar itself, indicated a generally positive response to the process and content, with some particularly enthusiastic comments. The interviews, conducted some months after the main seminar, yielded indications of more long-term benefits from the seminars. The students interviewed, without any particular prompting, provided answers to questions that indicated that they were still very mindful of the major issues raised in the seminar and had since developed specific practices regarding their learning that were more consistent with a deep and creative approach.

> ... if you find something and you invent it ... if you explain it to yourself in some kind of way, it'll stick to you more than if someone else has just explained it to you, so you understand that. You have to understand it in your own way to understand it.

> Tearing myself away from the textbook and looking at what you're doing ties in with things around us, the environment and sort of being more aware of where the physics lies rather than just separating it.

> ... so it's really good because you get back to the fundamental reason of doing physics. So with that kept in mind then you can go about doing the rest of the things. Like not minding all the slogging or anything because ... so I think that's really ... a really fresh approach. And not just to physics, but I found that it applies to my other subjects as well.

Several were clearly still intrigued with the questions raised in the seminar programme, and had continued actively to consider these questions against the background of the courses in which they were studying.

> I remember walking out thinking I was more confused than when I walked in. That I hadn't learnt ... anything directly related to physics, but it was somehow slightly inspiring in that [it] unlocked a few of the mysteries to learning, and it just put a fresher note, or fresher outlook on physics. The fact is that yes, everybody is confused about physics, and that if you're not afraid of it [the confusion] it will help you, help you to learn.

> I think now with the help of [the seminars] that physics has become more of a lively subject, something that's continually developing, changing, and you can ... something that you can invent for yourself too ...

> It was nice to actually think, because going to lectures was—well I found when I first came here I was deliberating between art and science. I chose science and suddenly found it very ... almost impersonal. It was just a load of

formulas and notes ... and there was not scope for creativity ... so that's what I enjoyed just going to these sessions.

8. Conclusions

The programmes detailed here indicate some of the potential ways of reducing the constraints/increasing the motivation of students to be creative in their thinking. The first two indicate the importance of the assessment device in testing for the sort of thinking required, extrinsic motivation, whereas the seminar programme was meant to motivate intrinsically. It was not the intention of any programme to address creativity as something additional to the existing curriculum, but rather to see creativity as inherent to the learning process, and to extend the application of this creativity to other matters. As in other pursuits labelled 'creative', engagement and responsibility are essential co-ingredients. That students recognize their authorial role in the development of their knowledge does make a recognition of responsibility for learning more pressing. We are not in a position to make this recognition inevitable, however; we can only claim to 'foster' creativity, rather than think we can teach it.

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