Cultivation of critical thinking in undergraduate engineering education

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INTRODUCTION

The quality of students' and engineers' thinking, and how they think, determines the quality of what they design, produce or make. Moreover, students and engineers today largely work with, and unquestioningly contribute to, the policies and agendas of the socially accepted market driven, pro-development standpoint [1]. So, in addition to the importance of critical thinking during technical development, critical thinking is also important to positioning students and engineers from a stance of social justice, and to be able to question the efficacy of developments. Just as is found in many professions, engineers now need, more than ever, strong critical thinking skills to deal with a world of increasingly rapid change and complexity.

This work is concerned with examining what it means to teach critical thinking, and, how this can be achieved effectively. There is a definite need to help students develop higher-order thinking skills, i.e., to do something more sophisticated than recite back facts they have memorized from lectures or textbooks [2], sometimes with little required analysis. What is hoped for as the outcome to this work is a major change in how students respond to problems and to give them the tools to think critically. Justification for the inclusion of critical thinking in the curriculum is well

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supported in the literature [3,4] and by many national commissions [5,6]. Yet when trying to implement critical thinking as an explicit goal in undergraduate engineering, there does not seem to be a well-defined scheme to ensure success. This may be in part, due to a lack of a good method to assess improvement in critical thinking [2].

It has been concluded that most students already consider themselves as effective critical thinkers, and faculty claim that critical thinking is a primary objective of their course [7], which may or may not be self-delusion. Also, it has been quickly recognized that although workshops and seminars on critical thinking have their place to initiate awareness, a systematic semi-implicit approach over a period of time is very necessary to cultivate critical thinking [8]. That is, once the principles of critical thinking are grasped and, importantly accepted by the student, then a period of time is necessary for cultivation, practice and hopefully becoming second nature.

To improve, or even to initiate critical thinking, a model first needs to be developed, capable of analyzing and evaluating the way engineers think, and hence this model applied appropriately. The general consensus found in the literature is that an explicit initial course on developing critical thinking skills is needed [9,10] followed by reinforcement. It is this type of approach which is developed here, where the critical thinking course is followed by a preliminary initiative to cultivate more and systematic critical thinking within various engineering modules found in an undergraduate engineering course.

In the rest of this paper, a discussion will be given of critical thinking in general, comments on developing an initial course on critical thinking, and how critical thinking may be reinforced throughout the rest of an undergraduate engineeringcourse. A section is also included summarizing the results of a discussion on how students view critical thinking in relation to themselves.

1 INITIAL THOUGHTS ON CRITICAL THINKING

To solve tough problems of society, especially when they are technological, creative engineers are needed [3]. It would seem that the responsibility of schools of engineering in universities, and also in society’s best interest would be to create creative engineers. Part of the problem of not dealing with critical thinking at undergraduate level, of course, is the tendency to push more and more information into each module so that just covering the syllabus material is all there is time for. Also faculty do not get personally rewarded for innovative teaching at the same level as research [8] so providing little incentive otherthan personal satisfaction. While there are many innovative ideas and trends within today’s teaching [11,12,13,14], there is still the tendency to over-use the lecture-homework-quiz format. This is indeed an efficient method of delivering knowledge and skills, but it has never been shown to be effective at producing the critical, innovative thinking skills needed to solve difficult technological problems. For critical thinking to be included in a meaningful way within engineering education undergraduate teaching and learning, it is argued that the following premises could give a basis for development:

- Defining what ‘critical thinking’ actually means and entails.
- Certain techniques have been identified by education theorists and psychologists, which have the possibility of stimulating creativity if integrated properly into the more traditional forms of instruction.
- While it is recognized that an initial course may be desirable/needed on critical thinking, the techniques mentioned above must be introduced throughout the curriculum.

- The methods intended to develop creative/high-level thinking must not take up too much time. As much integration as possible, with the existing syllabus, is desirable.
- Establishing a method to assess, however crudely, to measure 'critical thinking ability'.
- Faculty should form workshops to discuss the sharing/development of techniques designed to encourage critical thinking.

2. DESIGNING A CRITICAL THINKING MODEL

Building on the premises listed in the last section, a summary of the research is now given which contributed to a course on critical thinking plus a strategy to implement critical thinking throughout an engineering undergraduate course.

2.1 What is critical thinking

Different definitions of the term 'critical thinking' abound in the literature [15,9,16] and this variability may in fact impede progress on all fronts [17]. Most of the definitions share some basic features and probably address some aspect of critical thinking [18]. In the face of so many definitions some authors go for a 'consensus definition' and others go for one that meets their needs and consistency in applying it [2]. For example, Baillie [19] explains critical thinking from the point of view of outcomes and at the beginning of her course she explains "students will be able to demonstrate an ability to think critically and reflexively not only about engineering practices in the abstract but about their own work in this unit; assess and apply different views of the relationship between science, technology and society; consider rights, justice, freedom and ethics and illustrate their relation to engineering practice; and compare and critique local and global technological practices". It can be taken from this lengthy definition that critical thinking goes beyond thinking clearly or logically and actually looks in depth at various relevant concepts by exploring such things as underlying issues, loosely connected issues or seemingly unconnected issues.

2.2 Initial critical thinking course

An initial course to introduce students to ideas which should improve their thought was devised. The course is based on Paul's critical thinking model [20]. The model, shown on *Fig. 1* has the goal of producing a mature engineering thinker.

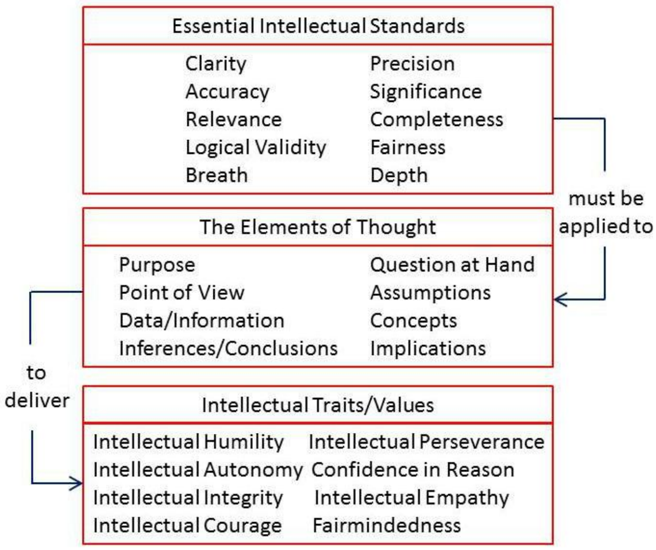

Fig. 1. Paul's critical thinking model [20]

The critical thinking course lasted one semester in the engineering undergraduate degree preparatory year (Level 0) and consisted of lectures, group discussions, and practicing analyses. Engineering design was used as the vehicle to introduce elements of critical thinking.

The course actually starts with the third grouping, i.e. lecturing on discussing 'Intellectual Traits/Values' in relation to engineering practice, followed by an introduction to 'The Elements of Thought',where students start analysing how they think and how others think. Lastly the 'Essential Intellectual Standards' are lectured on, discussed and practiced using exercises based on engineering design. Each of these sections is now briefly discussed.

2.2.1 Intellectual traits/values

The overall objective here is to make students aware that professional engineers must cultivate personal and intellectual values, so that they think with insight and integrity. For engineers certain distinct issues come to the fore within each category:*Intellectual humility* admits to ignorance and being truthfully sensitive to what you know and what you do not know. *Intellectual autonomy* is the ability to think for oneself while adhering to standards of rationality which is important so as not to accept other viewpoints without questioning.*Intellectual integrity* means that you do not have double standards and you hold yourself to high intellectual standards expected by you in others.*Intellectual courage* is when you have strong views, which may be unpopular, and you are willing to express these views to your peers.*Intellectual perseverance* is the ability to work through complex and frustrating tasks. *Confidence in reason*is a mixture of being open-minded regarding other peoples' views, encouragement of other people to have a view and the ability not to distort views to support my own position. *Intellectual empathy* is important as it helps the engineer grow and mature as he/she takes on different views. *Fair-mindedness* is the ability to treat all viewpoints without bias or prejudice and so be able to make judgments appropriately.The method of delivering this part of the course was to first give anintroductory lecture followed by small group discussions using appropriate lists of questions. At the end of each session, the complete cohort came together to summarise the findings.

2.2.2 The elements of thought

In this section of the course the aim was to help students evaluate how they think, or how others think. The reasoning behind the structure of this part of the course is that whenever we think, we think for a *purpose* within a *point of view*, based on *assumptions*, leading to *implications* or consequences. We use *data,* facts and experiences, to make *inferences* and judgments, based on *concepts* and theories, to answer a *question* or solve a problem. A similar approach for delivery was used as for the first section of the course, where introductory lectures were given, followed by discussions and exercises based on engineering design.

2.2.3 Essential intellectual standards

Such standards need to be applied when one is interested in checking the quality of reasoning about an engineering problem or project. To think professionally as an engineer means having command of all of these standards. As with the last section delivery here was by introductory lectures, followed by discussion and exercises based on engineering design. A brief list of typical questions associated with each of the intellectual standards is given in *Table 1*.

Table 1. Typical design questions associated with intellectual standards

Clarity	- What are the success criteria? - Have assumptions been clearly defined?
Accuracy	- Are the modelling assumptions appropriate? - Has the test equipment been calibrated?
Relevance	- Does the design address the requirements? - Has irrelevant data been included?
Logical validity	- Is the design decisions based on appropriate analysis? - Are there any hidden assumptions?
Breath	- Have alternative approaches been considered? - Have end-of-life issues been considered?
Precision	- What are the accepted tolerances? - What are the error bars or confidence bounds?
Significance	- What are the design drivers? - What impact will there be on the market?
Completeness	- Is there room for further development? - How could the next version be improved?
Fairness	- Are vested interests influencing the design? - Has public/community interests been considered?
Depth	- How far have the complexities been accounted for? - Has growth capability been addressed?

2.3 Reinforcement throughout the undergraduate course

In addition to the 'Initial Critical Thinking Course', it is thought imperative to integrate critical thinking into each of the modules found in the engineering undergraduate course. The support of faculty member is indispensable here, as they have the power to include critical thinking or not in their modules. Seminars/discussionswere held for the Faculty on the inclusion of critical thinking in the classroom at the beginning of the academic year and several times during a semester derived from the theory put forward by Glaser [21],who has suggested five components critical to the reinforcement of critical thinking.

- The first component, specific knowledge, was based on the belief that knowledge was necessary for critical thinking. Engineers must have a knowledge base on which to build their critical thinking skills.
- The second component is experience. Engineers the know-how that allows for instantaneous recognition of patterns and intuitive responses in expert judgment.
- The third component is competencies. General critical thinking competences are related to the scientific process, hypothesis generation, problem solving, and decision-making.
- The fourth component is attitude, including confidence, independence, fairness, responsibility, risk taking, discipline, perseverance, creativity, curiosity, integrity, and humility; and intellectual standards, including clarity, precision, specificity, accuracy, relevance, plausibility, consistency, logicality, depth, broadness, competence, significance, adequacy, and fairness.
- Finally the fifth component is professional standards so as to accentuate safe, competent engineering practice.

Three levels of critical thinking were identified in the seminar. An initial level where answers to complex problems are right or wrong and there is only one right answer. A second level was the complex level where students could recognized options and alternatives, but did not make a commitment to any one solution. The final level, and ultimate goal, was commitment by the students to a solution. At this level, students (engineers) must be encouraged to choose an action or belief based on the options identified at the complex level.

The Faculty was then encouraged to think about the following so as to facilitate better integration of critical skills into their teaching and learning [22]:

*Table 3.*Factors that Influenced the Development of Critical Thinking Skills

Pedagogical Factors that Influence Critical Thinking Development	
Curriculum Design	- Acquiring foundational concepts - Progressing from simple to complex concepts - Applying learning in the laboratories/projects
Integrative Learning Activities	- Tests - Case studies - Simulations
Personal Factors that Influence Critical Thinking Development	
Curiosity Confidence Perseverance	
Other Factors that Influence Critical Thinking Development	
Faculty support Reinforcement, both in and out of the engineering programme	

3. DISCUSSIONS WITH SELECTED STUDENTS

Twenty students were selected to give preliminary feedback on the impact of the above work so far in the form of a group discussion. As already alluded to, most of these students already thought of themselves as critical thinkers before the year started. This could be a widespread self-delusion, and it is clear work needs to be done to find out how true this self-opinion is. If it is untrue, then a process of changing attitudes and intellectual disposition, and, engendering a willingness on the part of the students to dedicate themselves more to thinking critically must ensue.

The majority of students thought the initial course on critical thinking quite cumbersome and unnecessarily long. They thought that a more condensed message, more dedicated to explaining and reinforcing the ‘Essential Intellectual Standards’, may be more effective. They explained that at the end of the day they need a brief list of rules and processes to go by, to give a manageable framework to work within.

Certainly the students recognised that critical thinking is a process and with practice and the correct attitude they would become much better at it. They all stated that more critical thinking within each engineering module they took must be increased.

4. CONCLUSIONS

Methods to cultivate critical thinking within engineering education have been examined and to some extent implemented. Essentially two major innovations have taken place, the first being the establishment of an initial course to students on what critical thinking is, why it is important an engineer has such a skill and how to incorporate this skill into everyday engineering practice. The second innovation was the creation of a seminar/discussion group for Faculty on integrating critical thinking into their respective engineering modules. Student feedback so far has asked for a more streamlined initial course and has encouraged course material in each module to include opportunities for more critical thinking.

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