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Assessment of Critical Thinking Skills in Engineering Education

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Abstract
The main task of engineers is designing and manufacturing of useful products. Rapid progress in science and technology is creating more innovative techniques and more advanced products. For today's engineering graduates to be successful, they must be able to solve complex and open-ended problems, and be capable of independent and critical thinking. Critical thinking (CT) can be simply defined as the analysis of available facts, evidence, observations, and arguments to form a judgment. Nurturing of critical thinking skills in students is generally deemed an uphill task by instructors at engineering universities. Quantitative assessment of CT skills and tasks is an even grayer area. This paper presents an overview of the different issues related to instruction and assessment of CT skills, and the various methods adopted, especially in the context of engineering education. Some of the more interesting issues discussed are classroom exercises for CT assessment; self-assessment of CT skills; CT assessment design, quantification, and summative assessment; taxonomy of CT assessment; and limitations of standardized CT assessment. This brief but in-depth review can be useful for engineering students and instructors targeting the development of CT skills, and for other branches of education.

Keywords: Critical thinking; engineering education; assessment of CT; effective assessment strategies

Introduction

In a nutshell, engineering is the designing and manufacturing of useful products. Due to rapid advances, products are becoming increasingly innovative and complex [1,2]. Successful engineering graduates should have the ability to solve complex and open-ended problems, and to exercise critical thinking [3-5]. A group of United States companies published a report in 2006 [6] according to which employers rate critical thinking (CT) as the most highly desired skill of recent graduates. However, over 90% of the surveyed employers were of the opinion that college graduates were deficient in CT skills. Though hardly anyone disputes the importance of CT, it is quite evident that CT instruction is inadequately addressed in most college curricula. Even after years of university education, in courses that claim to develop higher-order cognitive thinking, many students graduate with limited CT skills [7].

Defining CT

Defining "critical thinking" has always been difficult, especially as it is often confused with ideas such as problem solving, higher-order thinking, and reasoning [8]. In a survey covering 57 colleges and universities in California, almost 89% of the faculty asserted that CT was a primary instructional target. However, only about 19% of the instructors could adequately define CT critical thinking [9]. The Delphi study conducted in 1990 by the American Philosophical Association (APA) defined critical thinking as "purposeful, self-regulatory judgement which results in interpretation, evaluation, and inference, as well as explanation of the evidential, conceptual, methodological, criteriological, or contextual considerations upon which that judgment is based" [10]. Since then, leading CT scholars have proposed their own definitions. Paul and [11] define CT as "the art of analyzing and evaluating thinking with a view to improving it." Peter Facione, the spearhead of the APA Delphi study, describes CT as "judging in a reflective

way what to do or what to believe" [12]. According to McPeck, a philosopher and CT researcher, CT is "the propensity and skill to engage in an activity with reflective skepticism" [13]. The most highly cited definition is the one by Robert Ennis, who is of the opinion that CT is "reflective and reasonable thinking that is focused on deciding what to believe or do" [14]. Ennis' definition captures the commonly noted dual nature of the critical thinking, consisting of 1) the use of rational criteria to judge the thoughts and ideas of others, and 2) the subjection of one's own thoughts to judgment by way of strong. This implies two distinct facets of CT: prudent and rational judgment of external ideas on the one hand, and unprejudiced self-analysis of one's own reasoning on the other (metacognitive and self-reflection skills).

Current Work

Over the last few years, the Mechanical Engineering (ME) program at our university has been attempting to explicitly include critical thinking as an intrinsic component of instruction in various courses. Qamar et al [1] presented a strategy to develop CT skills in engineering graduates, taking two core courses in the Materials and Manufacturing stream as case studies. In line with CT philosophy, course outcomes and objectives were revised, course delivery and instructional strategy were modified, and assessment plans were reworked.

The Industrial Engineering (IE) program at our university has now started to revise some courses with a view to inculcate CT ability in the graduates. A few of the course outcomes that definitely need critical thinking skills in some of the IE courses are mentioned below. Product Design and Manufacturing (PD&M) course: be competent with a set of tools and methods for product design and development; be aware of the role of multiple functions in creating a new product; understand the impact of PD&M in a global and societal context; etc. Facilities Design and Logistics course: make highly effective, efficient, and successful plans; develop, select and evaluate alternative facility layouts; reinforce specific knowledge from other courses through practice and reflection in an action-oriented setting; etc. Production Planning & Control (PPC) course: identify, analyze and solve PPC problems; work as a member and a leader in a team to solve complex PPC problems; access and analyze information related to PPC from various sources in an effective manner; prepare written report and give oral presentation on selected PPC issues; etc.

Though revision of course objectives and modification of instructional strategy are already tough tasks, devising appropriate assessment tools for critical thinking is perhaps the most challenging aspect of course overhaul. Presented below are some significant observations related to assessment of CT skills, from our own experiences in different ME and IE courses, and from published papers on this issue [15].

Instructional Approaches to CT

According to a recent study [16], three techniques stand out in improving critical thinking skills in students: discussion in small groups and at the full class level; problem-solving and role-play in complex real-world situations; and mentoring through one-on-one student-instructor basis. However, it is unanimously agreed teaching CT is difficult and context-specific, and there is no universal magic recipe. Disposition in CT refers to the attitudes and motivation that make CT a habitual practice. It has been suggested that the best way to teach CT dispositions is to model the behavior for students [12], provide challenging tasks, and let students observe others who are good in solving complex CT problems [17]. Metacognition is another key element of CT, encouraging

students to reflect on their own thinking. Students should be instructed about how cognitive activities occur and can be controlled. Just asking students to think why they have been given a certain academic assignment can propel them towards habitually questioning their thinking activities [18]. One of the greatest barriers in teaching and learning of CT skills is the issue of transfer. Students who successfully use CT in one domain may fail to transfer these skills to a new context or discipline. Studies show that it is best to explicitly teach and practice transfer in CT instruction [19]. This may require assisting students in recognizing that CT skills are necessary, in choosing the correct skill, and in applying it to different situations.

Reflective Judgment Model

Despite various challenges, some instructional strategies are quite effective in teaching critical thinking skills. The reflective judgment model of King and Kitchener [20] is built around the idea of ill-structured problems that "cannot be described with a high degree of completeness; cannot be solved with a high degree of certainty; and experts often disagree about the best solution, even when the problem can be considered solved." Ill-structured problems are best handled in a problem based learning (PBL) environment. Small groups of students are given problems based on real-life situations or case studies in their specialization. Knowledge is transferred by discussing the students' solutions, proven in many cases to improve critical thinking [21,22]. Not very different from the ill-structured problem model, the inquiry-based instruction model nudges the students to ask their own questions related to the problem, and then generate relevant solutions. This model furthers the metacognitive element of CT by encouraging students to identify their knowledge gaps and misconceptions and to come up with their own mechanisms for overcoming these shortfalls [23].

Concept-Mapping

This is another method that promotes critical thinking in both face-to-face and online teaching setups [24]. A concept map is a diagram or graphical tool that visually represents relationships between concepts and ideas. Argument maps or trees are adaptations of concept map, based on a visual display of relationships between arguments, evidence, and reasoning [25].

Quality Practice Hypothesis

Introduced by van Gelder [25], this hypothesis is based on the premise that CT thinking skills can be enhanced only through wide-ranging and meaningful practice. This requires the practice of cognitive psychology. For successful retrieval of useful and pertinent CT skills required in different situations, students should have ability to meaningfully recall and connect previous knowledge. Regardless of the practice methods used, the scholarly consensus is that gaining critical thinking skills is an effortful process that may take time. Instructors who explain that coming to a carefully informed conclusion will take more effort may find that students are better prepared for the additional mental exertion required to think critically [21,23].

CT Assessment Methods

Teaching and learning of critical thinking skills is an uphill but possible task, especially using effective instructional strategies as described above. However, measurement of CT capabilities presents an additional challenge. Some basic standardized tests for CT are currently practiced in different institutions of the world. These include the California Critical Thinking Skills Test [10], the Cornell Critical Thinking Test [26], and the Watson-Glaser Critical Thinking Appraisal [27].

Still, an across-the-board standardized test may not be suitable or practical in individual environments.

Multiple-Choice Questions

Many scholars and practitioners are of the view that well-designed MCQs can provide a reliable and valid measure of higher order thinking skills [28]. Morrison and Free [29] proposed four basic criteria for developing MCQs that promote and effectively assess CT. One, students should be asked for a rational justification for their answers chosen. Two, questions should be at a higher-order cognitive level of Bloom's taxonomy (above the apply level; including analyze, evaluate, and create). Three, students should be required to do multi-logical thinking: know more than one concept for a single question. Four, all MCQ options should be plausible alternatives, with one option being the best-fit.

Open-Ended Reflection

Reflection is considered to be a good tool for stimulation of critical thinking. However, assessment of open-ended reflection responses can again be quite demanding because of its subjective nature. Bourner [30] suggests that a good reflection should provide evidence of the ability to "interrogate experience with searching questions," without making judgments about their subjective experiences. Reflection type assessment strategies have been found to be more effective when accompanied by instructor feedback.

Best Practices for CT Assessment

Gleaned from published literature on effective instruction and assessment of CT [31], and based on our own experiences (though not comprehensive) with CT based course revisions, summarized below are some general recommendations to make assessment of CT skills more practical and efficient.

Treat CT as a multidimensional construct. Many researchers agree that CT requires both skills and temperaments related to reasoning. It is also believed that critical thinkers are self-regulated persons who use CT as a behavioral guide. It is crucial CT skills and dispositions are both assessed; a person may not think critically if the disposition is lacking [32].

Select important goals, objectives, and outcomes for CT assessment, in consultation with other faculty and in line with published literature on major CT goals. Another important step is to identify courses in the curriculum that are more heavily dependent on critical thinking. Tabulating a curriculum alignment matrix for the program can be really helpful [33].Three; make sure CT assessment is well aligned with instructional focus. The assumption that major CT objectives are already being achieved in a certain course may not be well founded. Specific outcomes should be identified that are relevant to the instructional focus of the course and to CT theory. Summative classroom assessments should be conducted at critical stages in the curriculum, rather than only at the start and completion of a program.

Try to employ the best and most appropriate assessment measures available. This requires an analysis of the content and form of instruction, the quality of measures, and the relevant CT aspects. Three of the most popular standardized multiple choice testing strategies were mentioned in the previous section. If no standardized tests are available for assessment of a specific CT skill,

instructors need to develop their own instruments, preferably as a focus group. Though not comprehensively researched, it is generally believed rubrics and similar qualitative measures are helpful in guiding and improving cognitive skills in students. When students are apprised of the of the scoring criteria at the beginning of the course, it can help students in improving the quality of their work, and promoting self-regulation [34].

Design assessments that are sensitive to changes in knowledge content. Learning is a process in which knowledge content changes over time because of experience or practice. Examples of assessment strategies that take this important factor into account are pretest–posttest, both of a simple nature, and with a control group [35].

Be cautious in interpreting the results of assessment, and in prescribing changes based on the results. Collecting and analyzing assessment data is an effective tool in deciding what is working and what is not. However, caution and restraint are essential in interpretation of results. Deciding to make changes in the program based on assessment data without giving due consideration to data quality can lead to far-reaching negative consequences. For appropriate interpretation of assessment data, several factors should be carefully considered, such as representativeness and size of samples, reliability and validity of measures, and the target objectives of data collection.

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