Critical Thinking, Reflective Practice, and Adaptive Expertise in Engineering

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Abstract
This synthesis paper examines the concepts of critical thinking, reflective practice, and adaptive expertise as represented throughout academic literature. The academic community generally considers each of these skillsets to be desirable attributes of engineering graduates and practitioners. Despite the trend of engineering programs across the country to embrace critical thinking, reflective practices, and adaptive expertise through mission and vision statements, the development of these qualities through education may be falling short. Lack of explicit exposure to and discussion of each concept may be contributing to the common inability of engineering students and educators to effectively communicate their understanding of each. In an attempt to contribute to the improvement of the situation, this paper aims to provide an individual evaluation of each topic as represented in the literature, a review of current operationalization techniques, and the current state of each topic within the field of engineering. Additional discussion builds connections by exploring relationships among the three topics, considers issues related to the topics within engineering, and offers possible areas of future exploration.

Introduction

Mission and vision statements for universities and colleges across the country underline the importance of critical thinking and related skills in higher education today.[1-8] Without explicitly using the phrase, sources such as ABET EAC and the National Academy of Engineering assert the need for engineers to be well trained in critical thinking skills.[9,10] However, a number of researchers[11-14] argue that many students show little to no gain in “critical thinking, complex reasoning, and writing skills”[11] over the course of their undergraduate educations. Despite consensus that one of the primary goals of college faculty should be to promote critical thinking, many professors fail to express a clear understanding of critical thinking or how to convey its use to students.[15] This represents a glaring roadblock on the path to producing effective engineers.

The difficulty in expressing a coherent understanding of critical thinking likely stems from the variability present amongst its numerous descriptions.[16-30] The definitions that exist lack an empirical basis, but a review and analysis of the various concepts may provide a foundation for discussion. Further, two additional topics may contribute significantly to the exploration of critical thinking: reflective practice and adaptive expertise. Critical thinking, reflective practice, and adaptive expertise have each received considerable attention individually in the academic literature, however, there appears to be a strong and deep connection present between these topics. Typically, each topic has been discussed in isolation or only in passing with respect to one another, so previous instances attempting to relate and link the concepts remain limited at best.

Ultimately, the goal of this paper is to begin a conversation about how a more thorough understanding of critical thinking, reflective practice, and adaptive expertise in conjunction with one another might contribute to the improved development of engineering students. To most effectively construct these relationships and their importance to the field, the paper shall be organized using the following structure: first, as the current literature typically considers each topic in isolation, the standard definitions of each will be presented individually; next, because the only way to determine the efficacy of our attempts to foster these abilities within our students necessitates an ability to measure, the existing operationalization techniques for each concept will be provided; subsequently, since improvements rarely occur without knowledge of the present state of affairs, a review of each concept in the context of engineering and engineering education will be considered; finally, all of the aforementioned content will be collectively analyzed to explore the relationships between each topic, the potential shortcomings of engineering education to sufficiently develop desirable skills, and how these shortcomings may be addressed, as well as additional questions this analysis may have aroused.

Definitions

Critical thinking lacks a clear, exact, and consistent definition due primarily to its highly philosophical nature. Some experts[16-28] attempt to give broad definitions, ranging from a problem solving methodology,[19] to an information filtration process,[28] to a simple 'frame of mind.'[20] Meanwhile, others define critical thinking through lists of specific skills related to reasoning, logic, and strategies.[18,29,30]

While each individual's definition and terminology differs, general trends tend to emerge.[18] This is perhaps best illustrated by Facione's Delphi report[31] in which 46 participants produced a collaborative definition of critical thinking as "purposeful, self-regulatory judgment" for "interpretation, analysis, evaluation, and inference," leading to a set of six main skills with corresponding sub-skills.

In addition to skills, several experts recognize that critical thinking involves a component of disposition or spirit, which leads an individual to approach all phases of life with reason and inquisitiveness.[20,21,32] The generalizability of critical thinking generates a greater degree of contention, but may be the most important consideration.[18,22] Some experts believe critical thinking cannot be developed in the absence of context[23,29,33] and may vary in form by subject.[23] Alternatively, others claim that while background knowledge may facilitate the process, critical thinking may be taught in a neutral context.[34,35]

Reflective practices relate closely to the disposition component of critical thinking.[36] Aristotle began discussions of reflective practices, but Dewey, Heidegger, and Schön receive the most credit for developing the theory.[37-44] The most important concepts involve transforming an unfamiliar or unexpected situation or surprise into something familiar by improvising a response using a 'reflective conversation' – 'reframing' the situation, considering possible actions, and 'listening' to the situation's 'backtalk' in an iterative loop. Schön suggested that individuals participate in non-reflective thought (or *knowing-in-action*), post-mortem reflection (or *reflection-on-action*), and *in situ* reflection (or *reflection-in-action*).[42]

The well-known foundations laid by Dewey, Heidegger, and Schön, however, apparently lack critical analysis and ironically fail to reflect upon themselves.[45,46] The call for a more reflective, critical analysis of reflective practice produced both practical and philosophical developments.[47] These developments have painted a clearer picture of levels of awareness, forms of surprise, bases of improvisation,[48] modes of reflection (based on levels of engagement,[48,49] temporal aspects,[50] epistemic purpose,[47,51] 'images',[52] and needs for extensions[53]), and differences between reflectivity and the deeper, more self-aware reflexivity.[51,53-55]

Developments have also unearthed potential limitations related to the use and study of reflective practices: man tends to avoid error and suppress negative feelings;[56] different cultures may possess different viewpoints toward reflection;[47] the standard utilitarian mentality potentially prevents anything beyond a practical grounding of reflection;[53] and finally, reflection may be fruitless if practiced individually rather than through discourse in a group setting.[47] Despite these limitations, reflective practices are still considered extremely useful in research and professional development,[51] as long as the practitioner employs it appropriately based on experience and background knowledge.[46,51]

Adaptive expertise consists of two core concepts: expertise and transfer. General or routine experts have extensive domain-specific knowledge and experience,[57] making them efficient, accurate, and fast with specific types of problems.[58] Transfer represents the ability of an individual to apply concepts learned in one context to a different, usually similar, context.[59] Adaptive experts, therefore, are like routine experts, but with the ability to transfer their skills. While general experts possess strong procedural knowledge, adaptive experts also possess strong conceptual knowledge.[60] Thus, adaptive experts utilize their understanding to flexibly adapt previous mental models to new situations.[61]

Adaptive experts are both highly efficient and highly innovative, while routine experts are merely highly efficient.[62] This difference derives from the adaptive expert's use of multiple perspectives and metacognition, as well as a disposition toward more rigorous learning.[63] Unfortunately, time constraints within the learning environment may lead to preferential adoption of procedural knowledge over conceptual knowledge, significantly hindering the development of an adaptive expert.[58,60]

Operationalization

In order to determine the degree to which engineers utilize critical thinking, reflective practices, and adaptive expertise and, more importantly, how engineering students develop these skills, measurement techniques for each prove necessary. A number of methods currently exist, though the lack of an empirical basis for what constitutes each topic imparts a degree of imprecision and uncertainty. Nonetheless, a quick review of the present operationalization techniques follows to provide background for subsequent discussion.

Researchers and practitioners have developed a variety of operationalization techniques for critical thinking over the years. Several groups have developed guides, frameworks, rubrics, and models to represent the skills of critical thinking – some based on expert opinions,[64-66] others derived through surveys of faculty perception of students.[29,67,68] Studies frequently measure student critical thinking through pre- and post- tests of relevant critical thinking skills,[69-76] though others use qualitative interviews and observations to determine the students' learning and perceptions.[70,77-79]

Though some of these methods consider critical thinking specifically within the context of engineering,[65,68-79] other methods attempt to measure general critical thinking skills, which can presumably predict future academic successes. These techniques are often based on multiple choice tests, the most common of which are the California Critical Thinking Skills Tests (CCTST),[80] the Watson-Glaser Critical Thinking Appraisal (Watson-Glaser CTA),[81] and the Cornell Critical Thinking Test (CCTT).[82] These tests have the potential to be useful for the general college population,[83] but critics claim the norm groups were insufficient.[83-90] Still, the Watson-Glaser CTA is generally the most accepted,[84-87] but the ultimate value of each instrument depends on the user's agreement with the corresponding operationalization items.[89]

Reflective practices often occur internally, thereby posing a challenging obstacle to measuring the attribute, but fortunately, verbalization facilitates reflection. The first attempt[91] to measure reflective practices consisted of a pencil-and-paper based test, analyzing a number of related attributes, and while a few currently applied techniques are test-like questionnaires,[92-94] the more accurate methods rely on interviews[49,95] and participant journals.[96] The interviews and journal analysis methods can determine an individual's reflective maturity fairly well, but require significant amounts of time to transcribe and code, and therefore lack large scale applicability, which is not an issue for the questionnaire style methods.

Adaptive Expertise has received less attention regarding operationalization. The How People Learn (HPL) Star Legacy Cycle establishes a framework that includes expertise and transfer, and therefore serves as a decent template for adaptive expertise.[97] Hatano's work formed the basis for a variety of rubrics to measure adaptive expertise in classroom settings.[98-100] Additional techniques compare pre- and post-tests[99-104] as well as devise equations.[104,105] Qualitative interviews with students[106] and surveys with students or faculty[107] can also provide an indication of a student's knowledge adaptation.

Implementation in Engineering

Exploration of these topics within the context of engineering often focuses either on how each topic pertains to professional engineers or, more commonly, how each can be implemented into the engineering curriculum and assessed. An emphasis on understanding how to optimally educate engineers to be critical, reflective thinkers and adaptive experts should enable academia to produce higher quality practitioners who can contribute to their fields earlier in their careers. Unfortunately, the ever increasing load of content knowledge delivered to students, the current delivery methods for that content, and large class sizes significantly limit the ability of students to adequately develop these skills.[36,108,109] Ultimately, the overall curriculum of engineering may require drastic changes to engage and challenge students to inquire and solve problems rather than to simply inform students what and how to think.[69,110] Of course the use of active learning techniques fosters these skills, but implementation is often conducted without explicit attention to critical thinking and reflection, a point we come back to in the Discussion.[111]

For critical thinking, the fact that engineering faculty tend to lack a clear, explicit understanding of the concept prevents students from acquiring a proper conceptualization of their own.[109] Various researchers have attempted to combat this obstacle by developing models and tables or lists of skills to teach and assess critical thinking.[29,36,109,112,113] With or without assistance of these models, academics have tried to incorporate critical thinking into the curriculum in the following ways: inclusion of stand-alone critical thinking courses;[112,114,115] emphasis on design based learning and problem based learning;[73,108-110,112-114,116,117] and infusion of writing assignments into coursework.[78,110,118,119] These attempts received mixed reviews from students in terms of preference, efficacy, and importance.[70,78,112,113,118,120]

A number of studies have compared critical thinking ability to various demographic variables and learning orientations. According to one study, a student's cultural background strongly impacts the expression of critical thinking skills.[121] The same study reported that students at predominantly black universities experienced more widespread development and that Asian students struggled to think critically. Another study reported higher levels of critical thinking for males than females.[122] Other studies have indicated positive correlations between critical thinking and information literacy,[110] self-efficacy, and effort,[122] no correlation between critical thinking and problem based learning,[73] and a negative correlation between critical thinking and achievement/grade focused learning.[120] Further studies indicate that individuals appear to implement critical thinking differently,[77] and critical thinking may or may not be generalizable across disciplines.[78]

The results of these studies could lead to further understanding of how critical thinking develops in engineering students. However, it should also be pointed out that the results of many studies were inconsistent or insignificant,[69,70,75,76] possibly due to failure of the testing apparatuses to truly measure critical thinking.[71] Until improved measures are developed and these inconsistencies are resolved, the implications of these findings for classroom practice remain unclear.

Reflective practices provide the bedrock for engineering ethics,[123] but also serve as a defining characteristic for success as an engineer due to the ambiguous and qualitative nature of problems within the field.[124,125] As these problems are often highly contextual and yet decidedly unique, poorly structured and ill-defined (or 'wicked'[126]), formal logic occasionally does not suffice, so engineers must frequently employ reflection in their judgment.[40,127-129] Additionally, the virtual experimentation of the design process, a critical element in many engineering disciplines, perfectly exemplifies Schön's reflective conversation and other views of reflection.[130-132] And perhaps more importantly, a critical evaluation of reflection within engineering, as initiated by van Gyn,[66] may lead to positive changes and challenges to existing power structures.[128]

In addition to benefiting the practicing engineer, reflective practices appear to contribute to the development of specific competencies and transferrable skills and to the transformation of values and attitudes.[108,128,133,134] However, debate exists regarding the need to teach reflection. Some experts claim that reflection is a purely innate disposition that improves over time without explicit instruction,[135] while others advocate the need to foster the behavior to achieve optimum results.[36,95,128,132,136,137] Unfortunately, instead of practicing proper reflection, many engineering students and instructors tend to focus on concrete events and often fail to improve adequately due to the lack of established mechanisms to measure growth.[132,138-140]

Attempts to infuse reflection into the engineering curriculum fall into four primary categories: verbally induced reflection; experiential reflection; retrospectively analytical reflection; and academically emancipative reflection. Verbally induced reflection is the processing of technical information into language or vice versa and includes the use of: journals;[124,129,141,142] notebooks;[138,143,144] papers, reports, and learning essays;[124,129,139,145-147] reflective readings;[147] group reflective discussion;[147,148] question-answer-techniques;[149] and direct mentorship.[150,151] Over time, students value these techniques[124] and show growth of engineering maturity and epistemology,[143] but tend to mirror the perceptions and values of their instructors.[138,150]

Experiential reflection refers to instances in which students reflect on situations experienced directly, virtually, or vicariously, such as: games or simulations;[144,151-153] problem based learning, project oriented learning, case studies, and combinations thereof;[133,140,154,155] design based learning;[132,156] service learning;[141,157,158] internships;[142] and development of programs and software.[159] Retrospectively analytical reflection seeks to determine relationships between previously obtained knowledge and experiences, including: creating diagrammatic representations of processes or concepts;[145,148,160] incorporating computer-based, student developed, or peer- and self-assessments;[161-163] and creating group reconstructed representations of experiences.[146] Academically emancipative reflection questions the very foundation of the current engineering education paradigm through modification of content, courses, and curricula. Engineering content can be delivered through web-based systems that prompt and foster user reflection;[139,164] entire courses can be designed around reflection[129,165] or taught in more interactive or novel formats;[166,167] and overall curricular design can be built on reflection.[145,168] Each of these latter three groupings of reflection involve the first or each other and present their own challenges and benefits.

As technologies advance, fields become increasingly interdisciplinary, and globalization continues, the need for engineers to be adaptive experts continues to grow.[169] The majority of educational programs develop routine expertise but fail to address adaptability.[169-172] Other fields have attempted to ameliorate this deficiency by integrating training, specifically in unpredictable environments that offer opportunities to adapt by linking previous knowledge to current situations.[173,174] Most adaptive expertise studies within engineering have been in bioengineering and related areas[63,74,99-101,103,104,175,176] and have employed the previously mentioned HPL Star Legacy technique,[100,101,104,171,176] challenge based instruction,[170] and design scenarios.[95,99,175,177]

Students matriculated in these courses generally showed growth in adaptive expertise during the course[98,99,102] and in longitudinal studies compared to students who did not take these courses.[98,99] Scholars suggested that growth in adaptive expertise relates to improvement in innovative solutions,[99] general knowledge,[100] factual knowledge,[101,104] and conceptual knowledge[104] and can serve as tools for measurement.

Discussion

The first matter of discussion pertains to the relationship among the three topics. The skills associated with critical thinking, reflective thinking, and adaptive expertise are most certainly all qualities an engineer should embody, but working through the connections may enable the academic community to instill those skills more effectively. First and foremost, it seems that critical thinking resides at the base of each of the other two concepts. The act of thinking reflectively certainly represents a modality of critical thinking. Considering the level of engagement classifications of reflective thinking provided by Schön and others,[42,48] it might appear that any thinking that is non-reflective is also non-critical and that all reflective thinking is also critical. Logically, this distinction would also suggest that all critical thinking must be reflective. However, an alternative classification system provided by Kember et al.,[92,96] states that 'understanding' occurs at a level above habitual action but below reflection, which may coincide with King and Kitchener's 'quasi-reflective' thinking.[49] This quasi-reflective level may be critical in nature, but is clearly somewhat reflective as well, so it is somewhat unclear as to whether critical thinking and reflective thinking can occur independently or if they are completely entwined.

Additionally, adaptive experts require conceptual knowledge beyond just procedural knowledge and then must transfer that knowledge to new situations, and hence, reframe the situation. Thus, even if the fuzzy distinction between critical thinking and reflective thinking is removed, an adaptive expert very clearly must employ both to obtain areas of deep conceptual understanding and to be capable of reframing that knowledge to fit a new circumstance. The fact that an adaptive expert must be skilled at employing both critical and reflective thinking, the ultimate goal of engineering academia should be to develop adaptive experts. Still, what it means to think critically and reflectively should be addressed somewhere, preferably early, along the way.

There are, however, other common threads amongst the three topics. Almost every description of critical thinking, reflective thinking, and adaptive expertise makes a point to mention some aspect of disposition. This suggests that some people may just be more naturally inclined to be critical thinkers, reflective thinkers, or adaptive experts. But does that mean that some individuals are less capable? Perhaps an examination of incentives to engage in critical and reflective thinking may be necessary to analyze this question, and more importantly, to find ways to encourage students to practice those skills. Another common thread – lifelong learning – clearly also requires this disposition.

A neurological approach to these comparisons could shed further light on the subject. A study conducted by Alexiou, Zamenopoulos, and Gilbert analyzed fMRI images of peoples' brains as they solved design vs. non-design problems.[178] When participants solved design problems, brain activity occurred in different areas than for analogous problems that lacked the design element. As noted previously, design is a significant component to engineering, and is strongly associated with critical and reflective thinking. It may be useful to study more fMRI images of individuals as they solve problems that are expected to promote critical thinking, reflection, or transfer in adaptive experts. Additional considerations could include comparing brain activity when answering questions that are said to promote critical thinking in a variety of subject areas. This information may help establish similarities and differences in each process.

Addressing how engineering programs should aim to produce adaptive experts who are strong critical and reflective thinkers requires the discussion of current engineering education issues and questions related to all of these topics, not all of which have easy or currently available answers. Perhaps most importantly, as Mina, Omidvar, and Knott emphasize, advances in technology and scientific knowledge have led to an ever increasing amount of content being taught to students.[108] Teaching students more in the same amount of time leads to the preference of procedural knowledge that prevents adaptive expertise.[58,60] Additionally, the increased content load discourages professors from incorporating active learning strategies into the classroom that explicate reflective or critical thinking. A student might have all the knowledge in the world, but if they are never given an opportunity to learn it at a conceptual level and integrate it with previous knowledge or to practice transferring that knowledge to new situations, that knowledge is useless. Thus, is it better to develop skills to become adaptive experts and hope students learn more content knowledge later in their careers, or better to deliver the content and hope students become effective thinkers later?

This question also presents another debate. If there are currently professional engineers who are adaptive experts and thinking critically and reflectively, without having an undergraduate curriculum that emphasizes those concepts, do they even need to be emphasized? If they absolutely cannot be taught, as Edwards and Thomas suggest,[135] then spending the time to do so would certainly be wasteful. However, the heavy influence of disposition might suggest that taking time to foster and encourage critical and reflective thinking could strengthen that disposition. This approach should likely occur most heavily at earlier stages of education to most effectively instill a stronger propensity and desire to think in these ways. Certainly, a better balance between developing skills and delivering content must be struck.

In order to effectively promote and foster critical and reflective thinking, instructors need a clearer idea of what constitutes each concept. An empirical approach to defining each term, specifically within the field of engineering, could be beneficial. This can be recognized through other fields that have a more consistent and concise understanding than that held by individuals in the field of engineering.[109] Part of the reason other fields have a stronger understanding of critical thinking is likely a consequence of increased and repeated exposure to the concept. Engineering programs, on the other hand, often claim to develop critical and reflective thinking, but fail to explicitly address what each means and how they intend to achieve this outcome, perpetuating the issue. Interestingly, an effort to do so might possibly attract a more diverse student body,[157] which can only benefit the field as a whole.

It is understandable, however, why these qualities have not received significant previous attention in the curriculum. The tools that exist to measure the development of each quality are not universally adopted, may not be highly relevant for each discipline, and may be extremely time intensive. Committing time to strengthen qualities is undesirable when their growth cannot be easily measured. Consequently, a concerted effort should be placed on the operationalization of critical thinking, reflective thinking, and most importantly, adaptive expertise before any significant advancements in implementation can be expected. If it is found that these skills vary by subject, then the development of discipline-specific, efficient methods for measurement can improve training significantly. If critical and reflective thinking can be strengthened in a neutral, general setting, and efficient tools can measure growth, then each process should be emphasized early in each student's education. Either approach should lead to engineering graduates who are stronger adaptive experts.

Conclusion

The importance of critical and reflective thinking in the field of engineering cannot be argued. The goal of developing adaptive experts who excel at thinking critically and reflectively is an admirable and important goal in engineering education. Engineers with training in critical and reflective thinking should be more capable in the increasingly complex, global landscape and will be more mindful of their impacts on society. While it appears that some individuals are more prone to be critical and reflective thinkers than others, and the skills may develop on their own with age and maturity, placing an emphasis on fostering those abilities can potentially attract students who may have otherwise rejected the field and should increase the speed at which new graduates can make meaningful contributions to their field.

Still, not all the concepts have been adequately established and developed. While engineering programs can attempt to improve their curricula to develop adaptive experts, until the entire subject has been fully illuminated through empirical research, attempts will only be speculative. Similarly, without adequately efficient and effective measurement techniques, it may not be reasonable to pursue these goals as the results of any implementation would lack sufficient evidence to properly support its claims.

Further, this introduces yet another element that should be part of the overall curriculum and may seem overwhelming given the constant increase in available content to be taught. The task to determine how to effectively incorporate opportunities to strengthen critical thinking, reflective practice, and adaptive expertise may be difficult, but certainly needs to be addressed. Specific courses could be taught with the pure intention of developing each skill, or the skills could be sprinkled into other courses throughout the entire curriculum by making classes more hands on or interactive, by including journals with the explicit purpose of reflecting, or using any of the previous techniques mentioned. Even simple repeated exposure to the topics should produce improvements.

It is also apparent that these considerations may produce even more questions, many of which may be difficult or impossible to answer. This path may be arduous and fraught with growing pains. However, no matter how these issues are addressed, the education of engineers can only benefit from a thoughtful effort of faculty to engineer the education system.

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