121st ASEE Annual Conference & Exposition
Indianapolis, IN
June 15-18, 2014
Paper ID #9806

Practical, authentic and sustainable development and assessment of critical thinking in engineering through model eliciting activities

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1. Introduction

Higher order skills such as problem solving or critical thinking are key attributes for graduates of any engineering program, are amongst industries highly desired skills for new employees and are considered a hallmark of a university education [1-5]. The application of critical thinking helps students solve ill-defined, open-ended, complex problems through the analysis and evaluation of information, evaluating arguments, and developing conclusions resulting from sound reasoning. These complex problems are typical of those encountered in professional engineering practice, and require the reflective, self-regulatory judgment exemplified by critical thinking. While most programs claim to develop critical thinking in some manner, deliberate development and direct assessment of critical thinking using some kind of conceptual framework is less common and quite challenging[3,6]. This is due to a multitude of factors: the lack of consensus on a definition of critical thinking, debate on whether or not critical thinking skills are generic or domain specific, the large number of available frameworks describing the elements, skills, traits and attributes of critical thinking and the difficulty in assessing a complex cognitive and metacognitive skill.

Within engineering, critical thinking instruction is typically provided in through the adoption of a previously established framework. While this method can be successful, there are some concerns regarding alignment between the application of critical thinking skills according to the model and the application of critical thinking skills to solve complex engineering problems. A similar misalignment exists in the assessment of critical thinking skills (CTS), and is of considerable concern. CTS are typically assessed through the use of standardized instruments. These tests are developed according to a guiding framework, which may not reflect the application of critical thinking skills in a manner consistent with how critical thinking skills are applied within the engineering discipline. These tests are typically divorced from course activities, provide little formative information and feedback and are viewed by students as extraneous and disruptive bringing about questions about their practicality and sustainable use in engineering undergraduate programs. Recently, there have been significant efforts in developing valid means for assessing key competencies, such as critical thinking, at the program or institutional level[7]. While this approach show much promise, these are only assessment materials and do not provide an all-in-one approach for developing and assessing critical thinking in engineering using discipline-specific performance tasks.

The primary objective of this paper is to provide a framework for the practical, authentic and sustainable means for simultaneous development and assessment of critical thinking skills in engineering using model-eliciting activities (MEAs). Model eliciting activities (MEAs) are performance-based, realistic problems used in the classroom that require learners to document their solution to problems using mathematical models, and document their processes for solving them. Studies have shown MEAs to be valuable in helping students to develop conceptual understanding, knowledge transfer, and problem-solving skills[8-11]. The common principles on which the MEAs are based upon are interwoven with aspects of critical thinking; the assessment and valuation of information; formulating justified assumptions and arguments; generating a valid, defensible model; presenting conclusions and recommendations resulting from analysis; and meta-cognitive reflective self-assessment to test and revise thinking. These elements can be carefully structured into a discipline specific framework for the development critical thinking in engineering as well as organized into a rubric for the assessment of critical thinking skills. Establishing an instructional framework and developing such a rubric will provide instructors with a practical, authentic, rigorous and sustainable means to simultaneously develop and assess CTS that better aligned with educational objectives and course experiences than standardized instruments.

In the following sections popular models of critical thinking used in engineering education and the corresponding assessments for each model will be presented along with the critical thinking framework constructed from the common principles of MEAs and the MEA as an assessment instrument. Discussion will pertain to the suitability and alignment of the frameworks and the practicality, accuracy and sustainable of the corresponding assessments, along with the advantages and disadvantages of using MEAs as a method for the consequent development and assessment of students' critical thinking skills.

2. Applying Critical Thinking in Engineering

In order to provide a common point for evaluation, comparison and discussion we will provide our view of the application of critical thinking in the context of solving complex engineering problems.

The reflexive, self-regulated, and reflective application of a structured manner of thinking to:

- Identify and accurately describe a problem or issue
- Determine the key issues be they technical, environmental or social
- Research, analyze and evaluate information pertaining to the problem assessing credibility, relevance, uncertainty and bias
- Evaluate supporting, conflicting and alternate arguments
- Develop solutions, conclusions or recommendations supported by data and analysis
- Consider the technical, environmental and social implications of their conclusions and recommendations

For the purpose of solving ill-defined, open-ended, complex problems

3. Critical Thinking Frameworks & Assessments

There are numerous critical thinking frameworks and assessments available for use. For the sake of brevity and the purposes of this paper, three frameworks and companion instruments (Cornell-Illinois Model, CLA Model and Paul-Elder Model) were selected due to their use within engineering education[12-14,11,15,16], accepted validity and reliability of the companion assessment[17,18], and the authors previous work.

The selected critical thinking frameworks each describe a different viewpoint on the complex construct of critical thinking. Each model is based on a working definition of critical thinking and provides a framework for the component skills, attributes, standards and dispositions according to the working definition. Many of these frameworks do not contain an explicit pedagogical strategy or developmental sequence for students; they simply provide a succinct definition of the construct and its components. However, a definition and framework form the basis of, and are essential to, the infusion of critical thinking into course curriculum. Each framework presented has a companion assessment each constructed their respective definition and framework of critical thinking. This leads to a wide variety in the format and tasks presented in the assessments, each with their own strengths and weaknesses. In the following sections each framework will be presented and companion assessment will be reviewed, discussing general critiques of the assessment, the alignment between the assessment task and complex engineering problems, how suitable the assessment is for use in engineering, and any additional concerns regarding the sustainable use of the assessment.

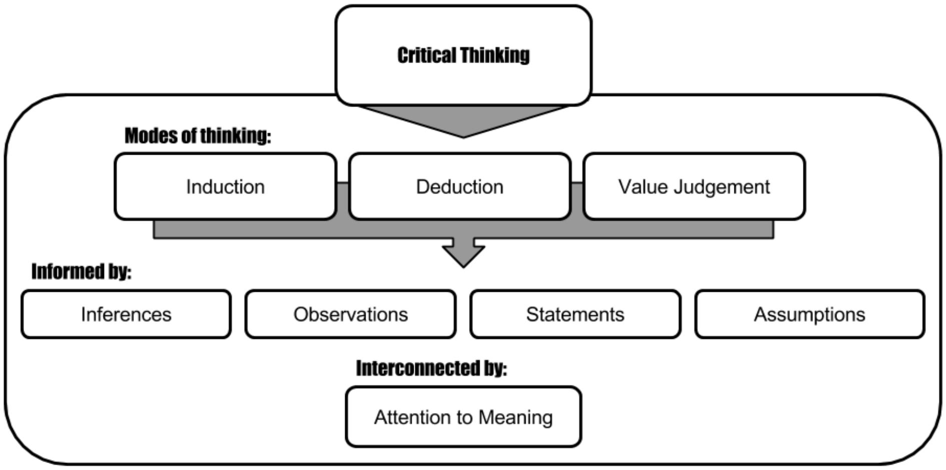
3a. Cornell-Illinois Model & The Cornell Critical Thinking Test: Level Z

The Cornell-Illinois model of critical thinking was developed and refined by Robert Ennis based on the following working definition of critical thinking:

> Critical thinking is reasonable and reflective thinking focused on deciding what to believe or do[19]

The model, illustrated in Figure 1, is divided and sub-classified based on three modes of critical thought (induction, deduction and value judging) and four methods on which they are based: the results of inferences, observations, statements and assumptions. Lastly, the model is connected by a common thread of attention to meaning which is interwoven throughout the four methods and three elements[19].

Figure 1. The Cornell-Illinois Model



The companion assessment, the Cornell Critical Thinking Test Level Z (CCTT) is a 52-item, multiple choice test. The CCTT measures aspects of critical thinking consistent with the Cornell-Illinois model organized into 5 categories[19]:

1) Induction
2) Deduction
3) Observation & Credibility
4) Assumptions
5) Meaning & Fallacies

3b. Critique of the Cornell-Illinois Model & The Cornell Critical Thinking Test: Level Z

The Cornell-Illinois framework, presents a vague picture of critical thinking as a set of cognitive skills that are applied to form a course of action. However, the type of thinking required in solving complex engineering problems is not linear in nature, requiring continual assessment, reflection and monitoring. These concerns have been addressed by Ennis in subsequent work[20], but raise important concerns about the alignment and suitability of the Cornell-Illinois model for use within engineering.

There are some potential issues with using a multiple-choice assessment of CTS, arising from the fact that the test does not assess dispositional aspects of critical thinking, or how individuals chose to engage in critical thinking. Multiple choice CT have been criticized as tests assessing verbal and quantitative knowledge and not critical thinking, since the format prevents test-takers from applying CTS to develop their own solution to the problem[21,22]. Additionally, multiple choice tests can only narrowly assess a single concept of thought in a question[22,23]. This is opposed to the real-world application of critical thinking to solve complex engineering problems which an individual employs a wide variety of concepts and skills to provide a comprehensive solution to a complex, interconnected problem encountered in engineering. There is also a significant misalignment between the tasks presented in the CCTT and tasks related in solving a complex engineering problem, engineering problems will seldom be as simple as selecting the appropriate response out of a list of possibilities. While that may exist at some point in solving engineering problems, it is the result of careful and well-reasoned analysis.

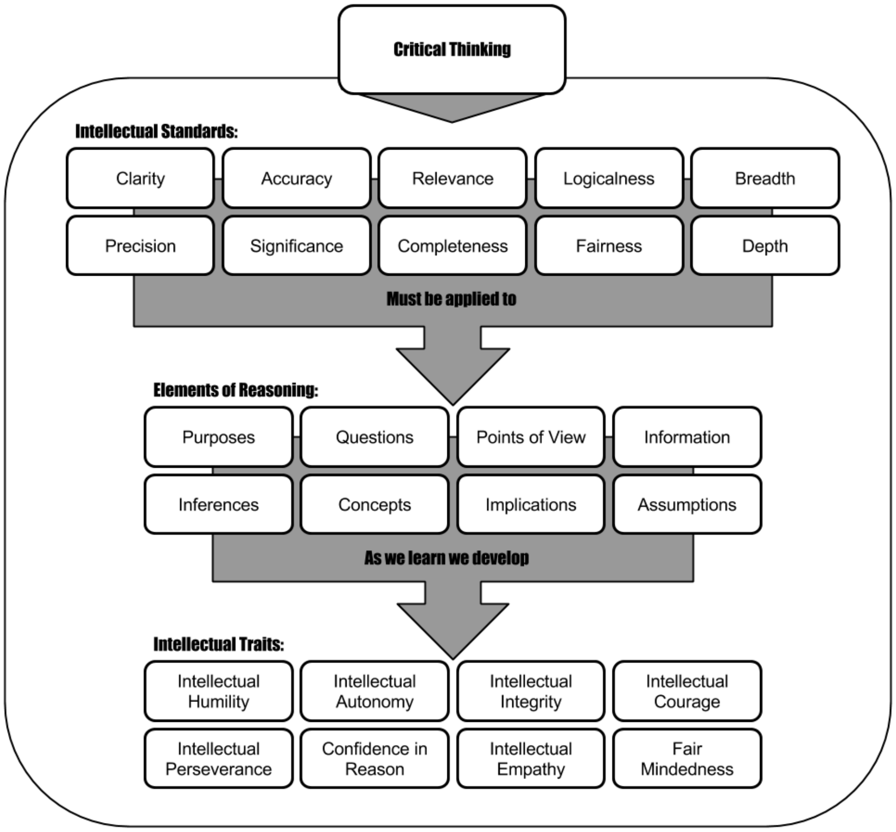
3c. Paul-Elder Model & The International Critical Thinking Test

The Paul-Elder model, developed originally by Richard Paul and further refined by both Paul and Elder[24]. The Paul-Elder model is based on the following working definition of critical thinking as:

> that mode of thinking — about any subject, content, or problem — in which the thinker improves the quality of his or her thinking by skillfully analyzing, assessing, and reconstructing it. Critical thinking is self-directed, self-disciplined, self-monitored, and self-corrective thinking. It presupposes assent to rigorous standards of excellence and mindful command of their use. It entails effective communication and problem-solving abilities, as well as a commitment to overcome our native egocentrism and sociocentrism.[24]

The Paul-Elder model divides critical thinking into three key components: elements of reasoning, intellectual standards and intellectual traits. The elements of reasoning are universal elements that inform and describe all reasoning or thought. The intellectual standards are standards applied to elements of reasoning or thought to interpret or assess quality. Lastly, the intellectual traits are desired traits or characteristics of a skilled practitioner of critical thinking. These three components are interrelated and each contributes to the development of a critical thinker. In the Paul-Elder model, critical thinkers apply the intellectual standards to the elements of reasoning in order to develop intellectual traits (Figure 2). There are two essential dimensions of thinking that students need to master in order to learn how to upgrade their thinking. They need to be able to identify the component parts of their thinking, and they need to be able to assess their use of these parts of thinking. These two essential dimensions, in concert with the intellectual standards, elements of thought and intellectual traits, can be organized into a rubric for the evaluation of critical thinking.

Figure 2. The Paul-Elder Model



The companion assessment, the International Critical Thinking Test (ICTT) is an essay-style test designed to provide an assessment of the fundamentals of critical thinking. The ICTT has two areas of focus. The first is to provide a reasonable way to measure CTS, while the second is to provide a test instrument that stimulates the faculty to teach their discipline in a manner that fosters critical thinking in the students[25]. The ICTT is divided into two separate forms: an analysis of a writing prompt and an assessment of the writing prompt. In the analysis segment (Form A) of the test, the student must accurately identify the elements of reasoning within a prompt. In the assessment segment of the test (Form B), the student must critically analyze and evaluate the reasoning used in the original prompt. Student responses are graded according to a rubric based on the elements of reasoning that comprise Paul's model of critical thinking[24]:

1) Purpose
2) Questions
3) Information
4) Conclusions
5) Concepts
6) Assumptions
7) Implication
8) Point of view

The ICTT was authored to have high consequential validity, such that the consequence of using the test would be significant and highly visible to instructors[26]. This encourages discipline-specific adoption of critical thinking and the redevelopment of curriculum that "teach to the test."

3d. Critique of the Paul-Elder Model & The International Critical Thinking Test

The Paul-Elder framework presents a discipline neutral view of critical thinking, and provides a comprehensive cognitive and meta-cognitive view of critical thinking through the standards, elements and traits[24]. This model is well aligned, suitable framework for use in engineering and has been adapted specifically for engineering[27], has been used to form a rubric for the evaluation of critical thinking in engineering[12,13,28], and has been used as a framework within MEA instruction[11].

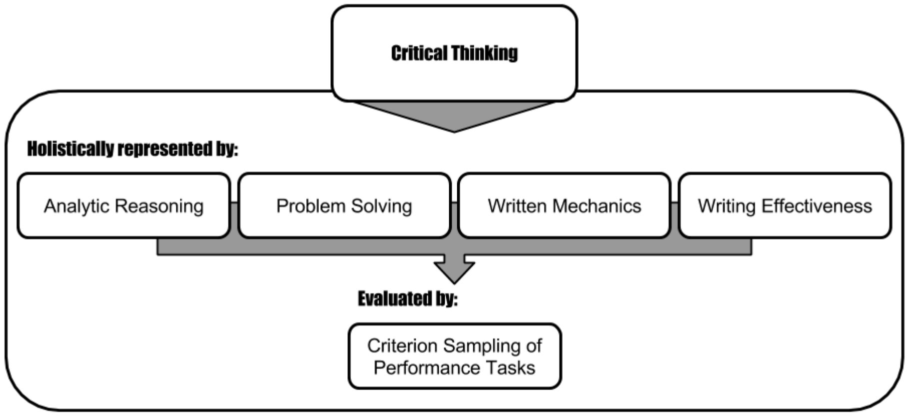
There are a few potential challenges that may be encountered with this style of test. First, the prompts task students with the recall-based identification and evaluation of the elements of thought. While these skills are of vital importance within critical thinking, the specific prompts cannot evaluate how students apply CTS in a real-world setting [23]. This highlights a misalignment between the task presented in the ICTT and what is expected in solving complex engineering problems. While the application of CTS to solve complex engineering problems requires correctly identifying the specific elements involved in critical thinking, the task on the ICTT does not require students to apply these skills in concert to generate a solution or develop a conclusion. Ultimately, the specificity of the questions may limit the breadth of response in test-takers, leading to a reduced inclination to engage in critical thinking[29]. Lastly, as with any essay-style or rubric evaluated test, inter-rater reliability (IRR) is a potential issue that should be considered when administering the test on a large scale[30].

3e. CLA Model & The Collegiate Learning Assessment

The description of the CLA model and the Collegiate Learning Assessment are based on the original CLA and subsequent versions used since 2000, and not the newest version the CLA+. The CLA+ offers improvements over the original CLA, addressing many critiques and concerns of the instrument. However, there appears to be little difference between the two versions regarding the manner in which they measure critical thinking.

The CLA model was developed for the holistic evaluation of critical thinking through problem solving. The CLA model holds that critical thinking assessment is best approached holistically, arguing that critical thinking cannot be broken down into component parts and measured. Instead, the CLA views the larger construct of critical thinking as being closely connected to and represented by several criteria or skills that students utilize in their responses on the test, as shown in Figure 3.

Figure 3. The CLA Model



The CLA model relies on a criterion sampling approach that is relatively straightforward and seeks to determine the abilities of a student by sampling tasks from the domain in which the student is to be measured, observing their response and inferring performance and learning on the larger construct. Shavelson (2008) explains criterion sampling by using the example of driving a car:

> For example, if you want to know whether a person not only knows the laws that govern driving a car but also if she can actually drive a car, don't just give her a multiple-choice test. Rather, also administer a driving test with a sample of tasks from the general driving domain such as starting the car, pulling into traffic, turning right and left in traffic, backing up, and parking. Based on this sample of performance, it is possible to draw valid inferences about her driving performance more generally.

The CLA follows the criterion sampling approach by presenting students with holistic, real-world problems. Through these problems, it samples tasks and collects students' responses, which are then graded according to a set of generic skills and formed into rubrics. In order to generate a successful response to the task, students would have to apply problem solving successfully, reason analytically, and write convincingly and effectively. Since these are all underlying components of critical thinking as defined by the CLA model, critical thinking ability can thus be inferred from student responses to test questions.

The Collegiate Learning Assessment (CLA) was developed and administered by the Council for Aid to Education (CAE). The CLA is constructed using the CLA model of critical thinking and problem solving as a foundation. Student response are graded using a series of grading rubrics, and are scored automated system on the on the following scales[31]:

1) Analytic reasoning
2) Problem solving
3) Writing mechanics
4) Writing effectiveness

3f. Critique of CLA Model & The Collegiate Learning Assessment

The CLA model is not an explicit framework, unlike the Paul-Elder or Cornell-Illinois models, which reduces critical thinking into constituent parts. Rather, the CLA views critical thinking in the broadest sense, as summarized by[1]:

> The ability to think critically—ask pertinent questions, recognize and define problems, identify arguments on all sides of an issue, search for and use relevant data and arrive in the end at carefully reasoned judgments—is the indispensable means of making effective use of information and knowledge.

This is consistent with the definition of critical thinking as applied to solve complex engineering problems, but lacks a defined structure to be used as an instructional strategy for critical thinking development.

The CLA consists of two distinct tasks, of which students generally complete one: a "performance task" and an "analytic writing task" containing two subtasks, "make an argument" and "critique an argument." There has also been some concern raised about the holistic assessment methods of the test not accurately measuring the component cognitive skills of critical thinking, and some critique on the grading method of the CLA[32]. There has also been some concern with the CLA results not being suitable for comparison at the individual student level, with testing results suitable only for institutional level measures[33]. A final concern is that the CLA is typically used to assess longitudinal development CT and is not recommended for measurement across a course experience, which affects the sustainable use of the instrument. Despite these potential challenges, the CLA is a comprehensive assessment, with the tasks requiring the identification, integration and use of multiple skills and critical thinking concepts.

The CLA is well aligned with the application of critical thinking skills to solve complex engineering problems. The tasks presented within the CLA are similar in nature to the complex engineering problems. Given a scenario, supporting information of varying pedigree on which to base analysis, provide a well-reasoned solution, conclusion or recommendation. While these tasks may not be fully representative of the scale and complexity of engineering problems, they require the application of the same skills involved in the more comprehensive engineering problems.

Overall, any of the reviewed frameworks would be suitable for use in developing CTS in engineering, due to their generic nature. However, explicit instruction in how to apply the elements of the framework towards solving complex engineering problems should be provided. The adoption of the companion assessments is more complex, as there is a distinct difference between the application of CTS in the assessment tasks and the application of CTS to solve complex engineering problems. This misalignment raises concerns regarding the accuracy and suitability of standardized instruments such as the CCTT and ICTT. The CLA, being a holistic, performance-based assessment of CTS, is well aligned with the application of CTS to solve complex engineering problems. Despite this alignment the CLA does not offer a means for the development of CTS, nor does it provide a suitable means for the sustainable assessment of CTS in a course experience.

With this in mind, in order to provide a valid, authentic and sustainable means to simultaneously develop and assess critical thinking within a course experience a realistic, contextually relevant, performance-based intervention, such as MEAs are ideal.

4. Model Eliciting Activities

MEAs have been used in engineering education at the university level for the past decade [10,11,34-36]. MEAs have shown promising results in developing students' topical conceptual understanding, information fluency, problem solving and communication skills[10]. MEAs require students to draw upon prior knowledge and often help to identify and address misconceptions in the course of learning and promote connections between information.

There is no explicit framework of thinking skills embedded with the MEAs, leaving the instructor free to carefully adapt and align a selected framework by which to provide scaffolding, structure and guidance for students to develop and apply to the process by which they solve the MEA. The MEAs are designed according to a set of six principles outlined below[35,37]:

1) Model construction: The activity requires the construction of an explicit description, explanation or procedure for a mathematically significant situation.
2) Reality: Requires the activity to be posed in a realistic engineering context and to be designed so that the students can interpret the activity meaningfully from their different levels of mathematical ability and general knowledge.
3) Self-assessment: The activity contains criteria that students can identify and use to test and revise their current ways of thinking.
4) Model documentation: Students are required to create some form of documentation that will reveal explicitly how they are thinking about the problem situation.
5) Construct share-ability and re-usability: Requires students to produce solutions that are shareable with others and modifiable for other engineering situations.
6) Effective prototype: Ensures that the model produced will be as simple as possible yet still mathematically significant for engineering purposes.

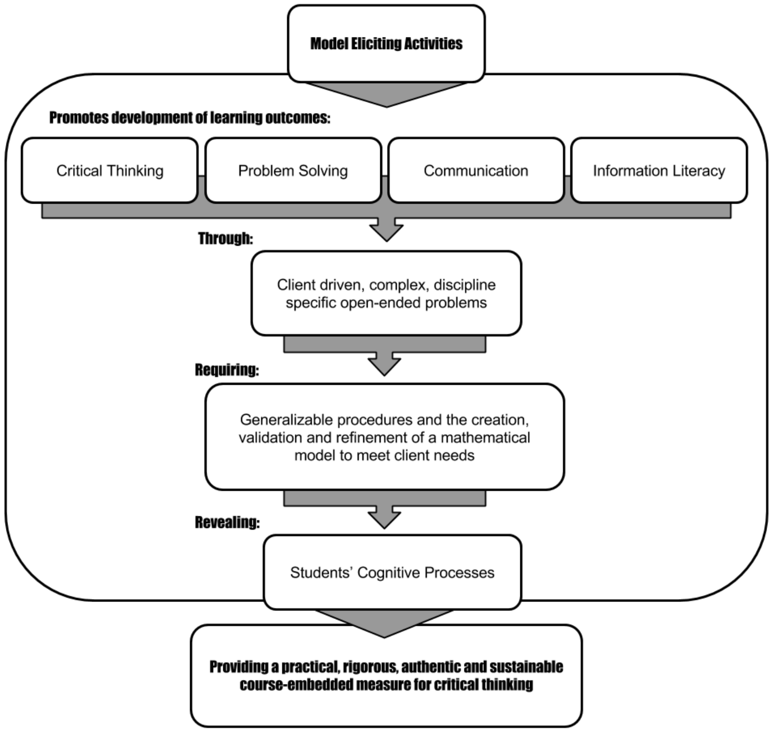
MEA instruction places a considerable emphasis on the process used to solve the problem and the reasoning and thinking students used to develop their solutions rather than on the product of that methodology. The solution of an MEA requires participants to apply and combine multiple engineering, physics or mathematical concepts drawn from their educational experience and previous background to formulate a general mathematical model that can be used to solve the problem. Students typically employ an iterative process approach to the MEA, first generating a model, testing the model and revising the model to develop a suitable solution[38]. The students' solutions to the MEA typically take the form of a comprehensive report outlining the process used to generate their solution to the problem.

There have been several studies investigating the impact of MEA instruction on student learning outcomes and general skill development. These studies have shown that MEAs:

1) Encourage a different perspective regarding the use of engineering concepts, with students applying concepts to achieve a broad, high-level solution rather than a low-level formulaic, rote approach[10].
2) Encourage students to work collaboratively and cooperatively as a group, honing teamwork and interpersonal skills and delivering a higher quality solution than individual submissions[39].
3) Encourage integration and synthesis of information and concepts spanning engineering and other disciplines[9].
4) Encourage reasoning and higher-order thinking skills through the ill-structured and complex nature of MEA instruction[40].

These benefits lead to a more meaningful learning experience for students by engaging them in an exercise that reflects professional engineering practice. This meaningful learning experience helps foster both higher-level skills and desired outcomes of complex problem solving, communication, information literacy and critical thinking, and provides a developing framework for the assessment of critical thinking by solving complex engineering problems outlined below in Figure 4.

Figure 4. Critical Thinking Assessment Using MEAs



A rubric for the assessment of CTS was developed, guided by the developed framework, our definition of CTS in solving complex engineering problems, the design principles of the MEAs and the results of previous MEA studies. Each outcome of the rubric measures a particular facet of critical thinking skills applied to solve complex engineering problems. Taken together, these form an overall measure for critical thinking skills used in solving engineering problems.

Outcome	Description
Information Summary	Accurately summarizes relevant information pertaining to the problem (background, contextual, content and methodological information), and includes an assessment of the credibility, uncertainty and biases of the information and its source.
Solution Generation	Creates, compares and contrasts quantitative models using approximations and assumptions generated from a justified problem solving process supported by information.
Interpreting Results	Evaluates validity of both the model and its results for error and uncertainty, drawing well-supported conclusions to support and strengthen the solution.
Critical Evaluation	Critically assesses conclusions on the basis of intellectual standards of clarity, precision, accuracy, relevance, logicalness, breadth, depth, significance, completeness and fairness.
Argumentation	Rationally supports claims and conclusions with data and comprehensive description of the context in which they apply.
Communication	Information is clearly and concisely presented, demonstrating consistent use of important engineering and technical reporting conventions, including organization, content, presentation and stylistic choices.

5. Discussion

Each of the frameworks for critical thinking presented in the previous sections, were developed on a sound and reasonable definition of critical thinking. Each of these definitions reflects application of critical thinking skills in solving complex engineering problems, however some are considerably more vague than others. Ultimately, the adoption of a critical thinking framework to provide explicit instruction within engineering is suitable, also long as the framework can be adapted or modified for use in an engineering context, and significant instruction is provided in how to apply the aspects critical thinking defined by the framework in a manner consistent with those expected in solving engineering problems.

Being able to reliably and validly assess critical thinking is paramount. Using standardized instruments may not be the best way to assess CTS in a course environment for a variety of reasons, including alignment, accuracy, practicality and sustainability. Standardized instruments are typically extraneous from course activities and are viewed as superfluous by students, and can lead to disengagement, motivational issues, and questionable assessment results[16]. The majority of these instruments must be purchased, which can be a barrier for courses without significant resources. In the case of essay based testing, time and resources for grading, with training and establishing inter-rater reliability included in potential costs[22]. The use of standardized instruments to assess critical thinking provides scant formative feedback to students, which is essential for the successful instruction and development of thinking skills, such as critical thinking[41]. These factors severely limit the practicality and sustainability of the use of standardized instruments in for the course based assessment of critical thinking.

Maintaining alignment between standardized instruments and instructional objectives is another area of concern. The prompts in standardized instruments are crafted in such a way to assess the dimensions of the framework on which they are based. An assessment structured in this fashion may only serve to measure how well the student applies CTS according to a framework, and does not measure the CTS required to solve complex engineering problems[22]. This calls into question the accuracy of the test for measuring critical thinking in an engineering context. It is similar to the criterion sampling example presented by Shavelson, that if you want to know if someone understands the rules and mechanics and can also drive a car, don’t give them a multiple choice test, have them perform a task that has them demonstrate the skills you want to assess. In the case of engineering, if we want to assess how engineers apply critical thinking skills to solve complex problems, provide a task that requires them to demonstrate those skills to solve an engineering problem.

The authors believe that the MEAs are such a task, and represent promising approach for measuring critical thinking in engineering. The assessment framework and rubric presented earlier presents a practical, course-embedded means for the authentic, rigorous and sustainable measure of critical thinking development and assessing critical thinking skills. The tasks presented in the MEAs are drawn from professional practise and require students to create and use a mathematical model of a physical system using a numerical computation tool (MATLAB) and to deal with professional issues including ethical dilemmas, conflicting information and incorrect/missing information. While each MEA requires students to employ different areas of subject knowledge, students are taught to approach all three MEAs using critical thinking skills. For example, students are guided to draw concept maps, question the credibility of information sources, incorporate a range of factors into their decision-making and consider the implications of their conclusions. These skills are what Paul calls "elements" of critical thinking – invaluable thinking processes involved in any complex problem-solving activity[24].

The embedded MEAs are virtually indistinguishable to students, mitigating motivation and engagement issues. Submissions are graded by teaching assistants and course personnel using the rubrics, with training and inter-rater reliability sessions provided, requiring no additional resources. Formative feedback is provided to students with each MEA submission, to help students improve in their application of CTS. These are clear benefits for the use of MEAs for a practical and sustainable means of assessing critical thinking in engineering over standardized instruments. Expectations are clearly presented to the students through the rubric; explicit instruction in the application of critical thinking skills to solve complex engineering problems is provided, alongside formative feedback to assist in CTS development.

Like any assessment, the MEAs are far from perfect. The development and integration of MEAs and including critical thinking skills in a course requires a substantial commitment and effort by the course instructor. While sample MEAs are available, these are not applicable for all disciplines, which requires the instructor to develop a MEA of appropriate context and difficulty for their course. The inclusion of critical thinking instruction requires that the instructor be very familiar with the framework and continually reflects upon, evaluates and revises their own thinking to best instruct their own students. MEAs are challenging for students, and providing effective formative feedback in an efficient and timely manner to help future submissions is difficult. As a partner to this, accuracy and reliability in grading is a concern and careful consideration should be paid to establishing and maintaining inter-rater reliability.

In conclusion, the authors believe that MEAs provide a platform for the practical, rigorous, authentic and sustainable development and assessment of critical thinking within a course experience. The MEAs provide a real-world engineering scenario in which students can practise the thinking skills that will be required of them by the profession, employers and society and simultaneously provide stakeholders an accurate and authentic measure of student performance. Future work includes establishing rubric validity and reliability, further developing the MEAs and the assessment framework, and investigating the use of alternate frameworks for critical thinking instruction. Lastly, it should be noted that while this approach is an improvement over standardized testing at the course level, program and institution-level assessment can still benefit from the use of standardized instruments or other approaches for the generic assessment of higher order skills.

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