AC 2010-1518: REFINING A CRITICAL THINKING RUBRIC FOR ENGINEERING

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Refining a Critical Thinking Rubric for Engineering

Abstract

The Accreditation Board for Engineering and Technology in 2000 revised accreditation criteria to require program assessment according to eleven outcomes that all require critical thinking skills. Critical thinking can be incorporated into engineering classes in a variety of ways including writing assignments, active learning strategies, project-based design experiences, and course redesign. Clearly, accurately and consistently assessing critical thinking across engineering courses is challenging. In 2007 the University of Louisville selected the Paul-Elder critical thinking framework for use in all undergraduate courses. However, few assessments have been developed using the Paul-Elder critical thinking framework.

Assessment of the ABET outcomes and assessment of critical thinking can be often be accomplished most effectively using rubrics. ABET defines a rubric as a set of categories developed from the performance criteria that define and describe progression toward meeting the components of work being completed, critiqued, or assessed. A holistic rubric assesses student work across multiple criteria as a whole while an analytic rubric assesses student work on each component of the assignment. Many papers have emphasized the importance of critical thinking in engineering programs and even more demonstrate the use of rubrics for assessing the ABET outcomes. Moreover, rubrics are available that assess critical thinking in engineering and different rubrics are available that assess critical thinking using the Paul-Elder critical thinking framework. However, no rubric, either holistic or analytic, was found that assessed critical thinking in engineering education using the Paul-Elder critical thinking framework.

The literature on assessing critical thinking in engineering and rubrics for critical thinking will be summarized and it shows that accurately and consistently assessing critical thinking across engineering courses is challenging. The process for developing and validating a holistic critical thinking rubric, based on the Paul-Elder critical thinking framework, created for use in engineering education courses as part of a longitudinal educational research project will be explained. The rubric, developed through a professional collaboration of individuals with expertise in the discipline of engineering and those with expertise in rubric development, will be described and the challenges in training faculty to use it will be explained. Initial validation of the engineering specific critical thinking rubric was done by engineering faculty using the rubric to assess an artifact from a first year Introduction to Engineering course. This process is described highlighting the importance of inter-rater reliability, uniform application of the rubric to critical thinking artifacts in all courses that are part of the longitudinal critical thinking assessment, and helping faculty understand the differences in grading an artifact and rating it according to the rubric.

1. Overview

Section 2 of this paper gives a brief background on critical thinking in general, a short review of critical thinking primarily with respect to engineering education, and explains why the Paul-Elder framework was selected by the University of Louisville as a specific model to guide the implementation and emphasis of critical thinking throughout the university and engineering curriculum. Section 3 discusses the relationship between critical thinking and the ABET outcomes, emphasizing why critical thinking and its assessment, both as an individual and group student skill is important for engineering programs. Section 4 reviews rubrics and distinguishes between holistic and analytic rubrics. Section 5 explains the process for developing and initial validation of a holistic critical thinking rubric, based on the Paul-Elder critical thinking framework. The critical thinking rubric was created for use in engineering education courses as part of a longitudinal educational research project at the university. Section 6 presents some initial assessment data using the rubric, and challenges related to using the rubric in evaluation of critical thinking in the study. Section 7 concludes with next steps in use of the rubric for the overall plan for assessment of critical thinking for the undergraduate engineering curriculum.

2. Critical Thinking

The term "critical thinking" is familiar to most engineering educators, but it is difficult to define easily. Paul et al[1] in one study found that 89% of teachers interviewed claimed critical thinking to be an important education objective, but only 19% were able to give a clear explanation of critical thinking. Ennis[2] defines critical thinking as: "Critical thinking is reasonable, reflective thinking that is focused on deciding what to believe or do." Scriven and Paul[3] give a more detailed definition: "Critical thinking is the intellectually disciplined process of actively and skillfully conceptualizing, applying, analyzing, synthesizing, and/or evaluating information gathered from, or generated by, observation, experience, reflection, reasoning, or communication, as a guide to belief or action." The three key elements of critical thinking thus are reason, reflection, and judgment. Fundamentally, critical thinking is thinking about thinking, a meta-cognitive process. The combination of reflection and reason leads to the final element, belief in the validity of a premise, process or solution to a problem, which also can lead to action. Critical thinking develops conclusions by deducing or inferring answers to questions and then reflecting on the quality of the reasoning; the end result is conviction, and in many cases action, based on those conclusions.

Bailin et al.[4] point out that much literature to that point characterized critical thinking simply as one or more skills, mental processes, or sets of procedures and that this characterization led to the view that critical thinking could be taught simply by practicing it. They emphasize the problems with this view and point out that critical thinking must be characterized in terms of specific performance criteria, that critical judgment is developed through applying knowledge in many contexts, and that improvement is made with frequent feedback and evaluation with respect to the quality of thinking demonstrated. The development of quality reasoning cannot be learned just by drill and practice in specific content areas, but requires opportunities for reflection and feedback as more involved thinking is required in a variety of contexts. All engineers consider themselves to be critical thinkers, and most feel they teach critical thinking as an inherent part of their instruction. Using critical thinking, or even demonstrating critical thinking, is not the same as explaining critical thinking and teaching students to think critically. A common vocabulary and conceptual constructs on critical thinking can help address the challenges of teaching critical thinking.

The Paul-Elder framework of critical thinking[5] has a formal structure and is a discipline-neutral schema (shown in Figure 1). It also addresses the concerns of Bailin[4]. The framework depicts critical thinking by applying Universal Intellectual Standards to the evaluation of typical Elements of Thought, with the goal of developing certain Essential Intellectual Traits in the thinker. The framework allows for the analysis and evaluation of thought, but more importantly, it provides a common vocabulary for those who want to discuss, evaluate, or teach critical thinking. The framework has been discussed specifically in light of engineering education[6].

The operational focus in the framework is the eight Elements of Thought which clarifies the building blocks of thinking; these building blocks are used by anyone who examines, analyzes, and reflects on intellectual work. These elements are embodied in eight categories of questions crucial to critical thinking:

(1) What is the purpose? (of the exercise, discussion or argument)
(2) What is the point of view? (of each participant, group or entity)
(3) What are the assumptions?(inherent premises of the argument)
(4) What are the implications? (of the reasoning or assumptions)
(5) What information is missing and needed to reach a conclusion?
(6) What inferences are being made?
(7) What is the most fundamental concept put forward by participants?, and
(8) What is the question that is being answered? (often forgotten in the battle)

Essentially, the Universal Intellectual Standards are the criteria used to evaluate the quality of the critical thinking, as described in detail in a subsequent section herein. According to the framework, applying the standards to the elements is what transforms common/general/everyday thinking to critical thinking. The overall goal is development of Essential Intellectual Traits that are characteristic of a mature critical thinker.

Faculty emphasis on critical thinking was investigated in a study by Paul et al. in the study cited previously. In this research, faculty members at 38 public colleges and 28 private colleges were surveyed, and the study included both education faculty and subject matter faculty. A total of 140 faculty members were asked both closed-ended and open-ended questions. A large majority of the respondents (89 percent) claimed that critical thinking was a primary objective in their teaching, but less than one tenth (only 9 percent) in fact were clearly teaching to imbue critical thinking routinely[1].

Cooney et al.[7] found a disturbing dissonance between the degree to which engineering and technology faculty at IUPUI believed they were incorporating critical thinking experiences in their courses, and the amount of critical thinking experience students perceived they were receiving. Analysis of faculty anecdotes and examples of teaching and learning indicated to Cooney and colleagues that a clear disconnect existed between what teachers considered critical thinking experience and what students identified as exercises in critical thinking.

Cooney and colleagues[7] reviewed research on developing critical thinking skills in engineering and technology students, and identified two significant activities that could be incorporated into classes easily and are very effective: writing based on reflection and learning through solving problems. In the first activity, students digest given information, analyze the content critically, similarly analyze the reasoning incorporated in the information, think about their own thinking, and then articulate their thoughts and/or value judgments.

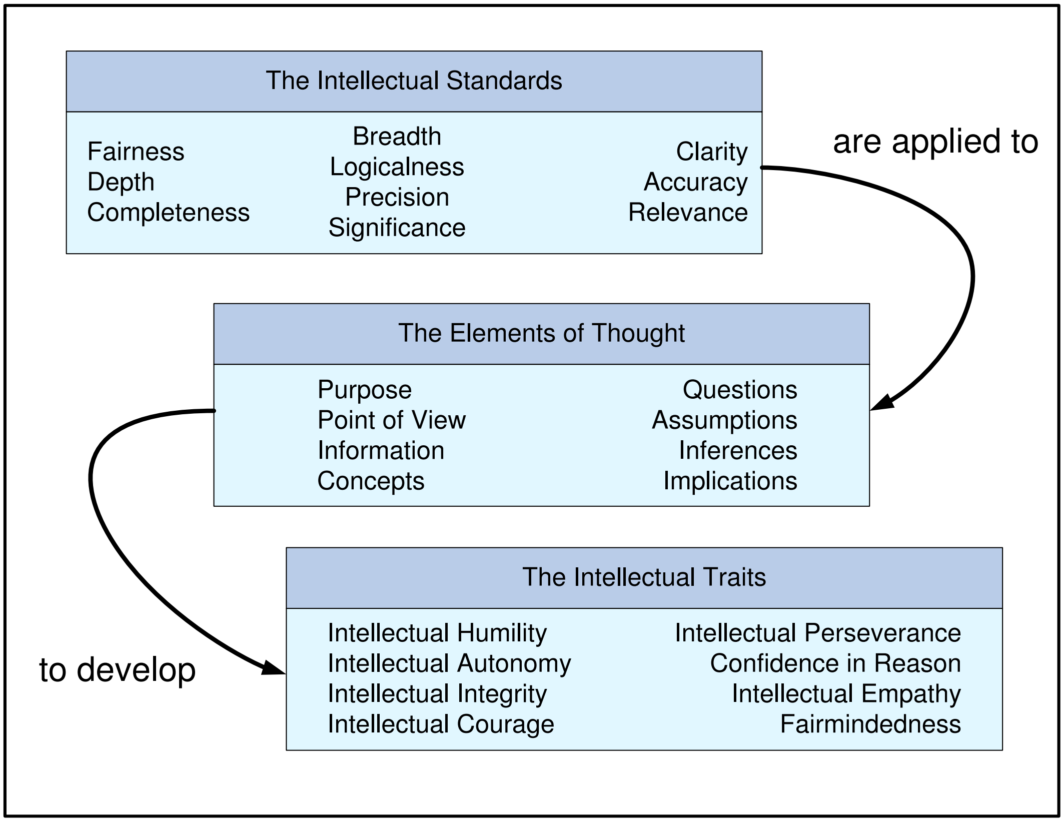

Figure 1. The Paul-Elder Critical Thinking Framework, adapted from Paul and Elder[5].

One method to implement such writing for reflection is to provide rubrics for evaluating open-ended problems, and then to provide feedback to help students revise their initial written reflections. Rubrics will be discussed in detail in later sections. The feedback is very important to refining thinking and cognition. Cooney et al.'s review explained how students can be asked to describe the design process in a reflective writing assignment, and how such reflection can be used to promote the design process itself. This involves the open-ended process of determining what is known, what has to be determined, an assessment and comparison of possible solutions or designs, and a final evaluation. Original work in open-ended design for engineering education can be found in Lunt and Helps[8] and Gurmen et al.[9] Damron and High[10] extended the research that involves writing and critical thinking to learning communities. Students in three sections of an Introduction to Engineering Course were paired in two sections of English composition with the other section not paired. A critical thinking model was used to structure writing assignments that required students to report on engineering concepts. Their initial results showed mean scores of paired students were higher in writing and critical thinking, but not with statistical significance. Further research in this area is planned.

Problem solving is the quintessence of engineering and learning through solving problems has been recognized for many years as a primary way to teach critical thinking[11]. Tsui[12] reviewed studies of how critical thinking has been taught and found that problem solving is especially effective. Engineering faculty have focused on developing critical thinking based on problem solving, especially since the adoption of the ABET 2000 criteria[13-15]. As mentioned previously, Cooney et al.[7] identified problem solving as a second major component in developing critical thinking skills in engineering and technology students. As taught most frequently in engineering courses, problem-based learning includes:

- Students working in teams
- Teams receiving an open-ended problem
- Students identifying the question to be answered and information needed
- Students gathering necessary information
- Teams discussing collected information, suggesting and evaluating solutions, and presenting team conclusions to peers and/or the instructor, often with feedback given and "re-evaluation" required.

Other research related to the development of critical thinking in engineering involves ethical decision making[16,17], conducting experiments,[18,19] and assessing the social impact of technology[20].

The "Backward Design Process"[21, 22] is an interesting approach to modifying courses to include critical thinking. Sgro and Freeman[23] describe three steps in the backward design process for engineering courses that include: first, identify the desired results or student learning outcomes; second, determine what will count as evidence that result has been achieved; and, third, develop the course to help students achieve the desired results. This method recognizes that not every concept introduced in a course is equally important. Consequently, the instructor begins by considering what concepts the students should take out of the course. That step identifies the "big ideas" in the course. The next question obviously deals with what would count as evidence that the students understand the key concepts. This is the point at which critical thinking emerges as essential. Evidence of understanding is much more than just recollection of facts. Comprehension of concepts requires, among other things, the ability to explain, interpret, and apply information and knowledge. Finally, the instructor must think about what learning experiences and teaching approaches will promote understanding. The identified teaching techniques and learning experiences then are incorporated in the course being designed.

Critical thinking skills allow students to more quickly assimilate subject-specific course content and also provide a framework that allows students to engage and respond to less-well defined problems, Tsui.[24,25] Tsui's research from four undergraduate institutions indicated that not only did writing assignments that required students to demonstrate a synthesis of material, evaluate arguments, and deduce conclusions improve critical thinking skills, but "re-writing" was even better due to the direct inclusion of feedback. The author points out that this study specifically excluded problem solving as part of the definition of critical thinking, thus there were no results for pedagogical improvements related to problem solving.

Any conscientious engineering educator must ask:

- How am I teaching/developing critical thinking in my students by modeling critical thinking skills, intentionally incorporating critical thinking skills in learning activities, and providing diverse opportunities for students to apply critical thinking skills in real-world situations?
- Are students aware they are learning critical thinking skills?
- Are students even aware of the need for critical thinking skills?

Before embarking on a program to improve the teaching and assessment of critical thinking in the J.B. Speed School of Engineering at the University of Louisville, program developers asked the engineering faculty members about the role of critical thinking in their teaching and in the practice of engineering in general. Faculty member responses were in line with what research had led the developers to expect: "Critical thinking is foundational to engineering education and to engineering practice." However, faculty responses also indicated that critical thinking was not being included as an explicit component in preparation and implementation in most course lectures and syllabi. Faculty members typically assumed that students could learn to think critically by watching them demonstrate critical thinking as they worked problems or discussed design issues. After further close discussion, most faculty members confirmed that they never explicitly discuss the thought processes behind problem investigation, analysis of situations, synthesis of designs, and evaluation of alternatives. The Engineering School embraced the Paul-Elder Framework as a means of introducing common labels and descriptions for all discussions of critical thinking and developed a program to inculcate critical thinking, overtly and intentionally, that extends from outreach programs to elementary and middle schools, throughout the undergraduate curriculum, to the culminating experience in engineering capstone design courses. In fall 2008, faculty at the Engineering School began a four-year educational research study to incorporate the Paul-Elder critical thinking framework transparently, across the undergraduate engineering curriculum; they also developed a plan for assessing results of the program. The program will operate as an ongoing feedback loop (assessment, revision, implementation, assessment, etc.) for evaluation of critical thinking skills, much as the ongoing Accreditation Board for Engineering and Technology (ABET) assessments function for engineering program curricula.

3. ABET Outcomes and their relationship to Critical Thinking

The ability to think critically is an important skill for practicing engineers, although in 2000, employers perceived engineering graduates to be particularly poor at critical and independent thinking[26]. The development of critical thinking, collaborative learning, communication, and leadership skills have been recognized to be as important for a faculty member to initiate as delivery of content[27]. One thoroughly versed in the Paul-Elder framework would argue that critical thinking is the foundation for all of the eleven program outcomes that must be assessed for accreditation by the Accreditation Board for Engineering and Technology (ABET). Engineering programs must demonstrate that their students attain the following outcomes: (a) an ability to apply knowledge of mathematics, science, and engineering, (b) an ability to design and conduct experiments, as well as to analyze and interpret data,(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability, (d) an ability to function on multidisciplinary teams, (e) an ability to identify, formulate, and solve engineering problems, (f) an understanding of professional and ethical responsibility, (g) an ability to communicate effectively, (h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context, (i) a recognition of the need for, and an ability to engage in life-long learning, (j) a knowledge of contemporary issues, (k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice. Although the term critical thinking is not used in any outcome, they all require "the intellectually disciplined process of actively and skillfully conceptualizing, applying, analyzing, synthesizing, and/or evaluating information gathered from, or generated by, observation, experience, reflection, reasoning, or communication, as a guide to belief or action", i.e. critical thinking[28]. Certainly many engineering educators have defined elements of life-long learning, including Shuman et al.[29] in their important paper that discusses how to teach and assess the ABET outcomes they define as "professional skills", outcomes (d), (f), (g), (h), (i), and (j). In their analysis, they proposed that attributes of life-long learning include the ability to: demonstrate reading, writing, listening, and speaking skills; demonstrate an awareness of what needs to be learned; follow a learning plan; identify, retrieve, and organize information; demonstrate critical thinking skills; and reflect on one's own understanding. However, a careful comparison of these attributes of life-long learning with the Paul-Elder model shows that they are so similar, as to be considered all critical thinking. Jiusto and DiBiasio[30] analyzed the effectiveness of an experiential academic program in preparing students for life-long learning through the acquisition of critical thinking, research, and communication skills which support self-directed learning. These two recent studies show the engineering community accepts that critical thinking is foundational to life-long learning. Thus, the assessment of critical thinking will compliment the assessment of ABET outcomes for engineering programs. The better thinkers students are, the better equipped they are to achieve the ABET outcomes. Students must be able to think critically as individuals and to assist teams in critical thinking. The assessment of program outcomes for engineering schools will be enhanced by strong, well-assessed critical thinking programs.

4. Rubrics

Assessment is a crucial component of any student learning outcome. Use of rubrics is one method for assessing students' critical thinking. At its most basic, a rubric is a scoring tool that lays out the specific expectations for an assignment. Rubrics are incredibly useful and flexible assessments that provide timely feedback, prepare students to use detailed feedback, encourage critical thinking, facilitate communication with others, help faculty refine their teaching methods, and level the playing field for students[31]. Assessing student work using rubrics provides a quick overview of valuable information about how students are progressing and areas for improvement.[31,32]

Rubrics contain 4 basic parts that describe the expectations of an assignment. The four parts of a rubric are the task description, scale, dimensions, and dimension descriptions. The task description summarizes the overall behaviors or performance outcomes for the given assignment. The task description is placed at the top of the assessment rubric and is preceded by a descriptive title for the rubric. Although the task description provides valuable information, the minimum essential part for the beginning of the rubric is the descriptive title. The scale describes various levels of student performance or achievement on the assignment dimensions. Scale descriptors can be either numbers or text. Numbers may either reflect the number of levels e.g. 4-3-2-1 or grade ranges for each level based on the institutions grading scale e.g. 100-93, 92-81, 80-73, 72-0. Textual scale descriptors should be clear, positive and developmental e.g. Exemplary-Competent-Developing-Unacceptable. Although there is not a preferred number of rubric scale levels, most rubrics have 3 to 5 levels. When constructing a rubric, the highest scale is placed in the first column or row and the other levels follow. The dimensions describe in simple but complete terms the parts of the assignment, similar to a task analysis. The dimensions are brief statements that represent the knowledge and/or skills students must demonstrate when completing the assignment but do not include statements about the quality of performance e.g., content not accurate. If the rubric is being used to assign a specific grade, then the dimensions can be weighted based on their relative importance to the assignment as a whole. The dimension descriptions are clear, complete statements of the highest level of performance expectations for each dimension at every scale level.[31] Figure 2 is a critical thinking rubric example with each part labeled.

Critical Thinking Rubric ← Descriptive Title

Task Description ↓

Assignment Description: The purpose of this assignment is for you to demonstrate your critical thinking abilities when addressing an engineering problem that was encountered in the "real world."

← Scale Descriptors

	100-93 (A)	92-81 (B)	80-73 (C)	72-0 (D, F)
Purpose And Questions (10%)	Clearly identifies the purpose including all complexities of relevant questions. 10--- 9.3 Points	Clearly identifies the purpose including some complexities of relevant questions. 9.2---8.1 Points	Identifies the purpose including irrelevant and/or insufficient questions. 8---7.3 Points	Unclear purpose that does not includes questions. 7.2---0 Points
Information (20%)	Accurate, complete information that is supported by relevant evidence. 20--- 18.6 Points	Accurate, mostly complete information that is supported by evidence. 18.4---16.2 Points	Accurate but incomplete information that is not supported by evidence. 16---14.6 Points	Inaccurate, incomplete information that is not supported by evidence. 14.4---0 Points
Assumptions and Point of View (20%)	Complete, fair presentation of all relevant assumptions and points of view. 20--- 18.6 Points	Complete, fair presentation of some relevant assumptions and points of view. 18.4---16.2 Points	Simplistic presentation that ignores relevant assumptions and points of view. 16---14.6 Points	Incomplete presentation that ignores relevant assumptions and points of view. 14.4---0 Points
Implications and Consequences (50%)	Clearly articulates significant, logical implications and consequences based on relevant evidence. 50---46.5 Points	Clearly articulates some implications and consequences based on evidence. 46---40.5 Points	Articulates insignificant or illogical implications and consequences that are not supported by evidence. 40-36.5 Points	Fails to recognize or generates invalid implications and consequences based on irrelevant evidence. 36---0 Points

↑ Weighted Dimensions

↑ Dimension Descriptions

Figure 2 Critical Thinking Rubric Example

Rubrics can be either analytic or holistic. An analytic rubric provides specific information about student performance on multiple dimensions so that their performance may be assessed on those dimensions across the scales. An analytic rubric allows for separate scale assessment of student performance on each dimension. A holistic rubric groups performance dimensions so that student performance is assessed as a whole across multiple dimensions. A holistic rubric is a broad, overall, general assessment of the entirety of the process.[33-35] Figure 2 is an example of an analytic rubric whereas Figure 3 later in this paper is an example of a holistic rubric.

As previously stated, rubrics are a scoring tool to either assign an individual performance grade for a specific assignment (analytic rubric) or an overall performance score usually for a program outcome (holistic rubric). Scoring rubrics, with their dimension descriptions are criterion referenced assessments that provide consistency across measurements and between raters. Artifacts are scored based on how closely they meet the stated criteria instead of how the quality of one artifact compares with other artifacts (norm referenced assessment).[36] An analytic rubric allows for variable scores across dimensions that are summed for a total score, or grade. A holistic rubric provides an overall score based on the scale dimension descriptors that most consistently describe the quality of the artifact.

Rubrics can also be either general or task-specific. A general rubric is used to assess a broad category of tasks, e.g. critical thinking, while a task-specific rubric assesses a specific task, e.g. lab reports or design assignments.[34,37] A rubric may also contain both general and task specific dimensions.[34] Table 1 contains sites to review available rubrics.

Table 1 Internet Rubric Sites

Site	URL
Opened Practices: The sites "Resources" tab has numerous rubrics on a variety of topics from different institutions and sites.	http://openedpractices.org
Rubistar: The site provides sample rubrics and templates for constructing individualized rubrics	http://rubistar.4teachers.org
Winona State: The site has numerous rubrics on a variety of topics from different institutions and sites.	http://www.winona.edu/AIR/rubrics.htm

5. Development and Initial Validation of A Holistic Engineering Critical Thinking Rubric

Critical thinking is a focus for the university's regional reaccreditation project and the School of Engineering's ABET accreditation criteria. The Paul-Elder critical thinking framework was selected to serve as the university-wide critical thinking framework for the regional reaccreditation project. Faculty in the School of Engineering designed and received Institutional Review Board approval for a 4-year longitudinal educational research project to assess engineering students' critical thinking abilities as they progressed through selected, key engineering course in the baccalaureate program. A key aspect of the research was a critical thinking rubric that could be used to assess student artifacts at each phase of the project. No existing critical thinking rubric was found that incorporated the Paul-Elder critical thinking framework for engineering. The engineering faculty decided to construct a critical thinking rubric based on the Paul-Elder critical thinking framework for use with the research project. Sevens and Levi[31] identify 4 steps in rubric construction that are reflecting, listing, grouping and labeling, and application.

The first step of rubric construction, reflection, focuses on the big picture, which is the overall purpose of the rubric and expectations for student performance.[31] In collaboration with the university's accreditation assessment specialist, engineering faculty with disciplinary and critical thinking expertise discussed the goals and desirable aspects of a critical thinking rubric. Using faculty with expertise in assessment, critical thinking and engineering was a purposeful strategy to enhance the content validity of the rubric. The overall goal for the rubric was a clear, straightforward, discipline-specific instrument that could be used to assess students' critical thinking abilities in written artifacts from freshman to senior engineering courses. Desirable aspects of the rubric included visual appeal and ease of use. Engineering faculty decided to construct a holistic rubric because it aligned with the research project purpose of an overall critical thinking assessment and was visually more appealing that an analytic rubric. A decision was made to have a four-level scale for the rubric, which is consistent with other university-wide holistic rubrics & minimizes the tendency to rate in the middle of odd number level scales.[33,38]

Listing includes a description of the various performance levels that are used to write the dimension descriptions.[31] Engineering faculty reviewed the Paul-Elder critical thinking framework to identify key Elements of Thought and Universal Intellectual Standards that would be applicable across engineering courses. The Elements of Thought selected to assess the components of the critical thinking were Purpose, Question, Information, Assumptions, Point of View, Implications, and Consequences. The Universal Intellectual Standards chosen to assess the quality of the critical thinking were clarity, relevance, completeness (depth and breadth), significance, logic, and fairness.

Grouping and labeling ends with complete dimension descriptions for each scale level.[31] The faculty began by writing the dimension descriptions for the highest (Level 4) and lowest (Level 1) scale levels. Afterwards, the two middle level dimension descriptions were written.

The final step of rubric construction, application, involves transferring the grouping and labeling information to a rubric grid.[31] Figure 3 is the rubric that was developed to assess undergraduate engineering students' critical thinking for the research project.

The holistic critical thinking rubric in Figure 3 has the identical dimension descriptions as the analytic critical thinking rubric in Figure 2. The two figures illustrate how the same dimension descriptions can be formatted into either an analytic or holistic rubric.

The holistic critical thinking rubric described in the previous section was first used to assess 176 written artifacts from freshmen in the Introduction to Engineering course who consented to participate in the research study. A total of 15 faculty volunteered to score the student artifacts throughout the research project. Faculty received a stipend to spend on any academic expense as a compensation for the time the scoring session would take over the 4-year length of the research project.

University of Louisville
JB Speed School of Engineering
Holistic Critical Thinking Rubric

Consistently does all or most of the following:

4	Clearly identifies the purpose including all complexities of relevant questions. Accurate, complete information that is supported by relevant evidence. Complete, fair presentation of all relevant assumptions and points of view. Clearly articulates significant, logical implications and consequences based on relevant evidence.
3	Clearly identifies the purpose including some complexities of relevant questions. Accurate, mostly complete information that is supported by evidence. Complete, fair presentation of some relevant assumptions and points of view. Clearly articulates some implications and consequences based on evidence.
2	Identifies the purpose including irrelevant and/or insufficient questions. Accurate but incomplete information that is not supported by evidence. Simplistic presentation that ignores relevant assumptions and points of view. Articulates insignificant or illogical implications and consequences that are not supported by evidence.
1	Unclear purpose that does not include questions. Inaccurate, incomplete information that is not supported by evidence. Incomplete presentation that ignores relevant assumptions and points of view. Fails to recognize or generates invalid implications and consequences based on irrelevant evidence.

Figure 3 Engineering Critical Thinking Rubric

The procedure for scoring the engineering student artifacts was similar to the procedure for scoring university-wide outcomes. Engineering faculty participated in a four-hour week day afternoon scoring session facilitated by four faculty with expertise in rater training and rubric scoring from the university's College of Education and Human Development. Table 2 contains the objectives and Table 3 contains the Code of Ethics for the scoring session.

To enhance reliability the faculty training included a practice session using the rubric to score student artifacts that were identical to those for the actual scoring session but would not be included in the final analysis. Faculty were debriefed after the practice scoring session in preparation for the actual scoring. The debriefing included discussions about reasons for and resolution to differing scores in addition to a review of the way to properly use a holistic rubric for scoring, not grading, student artifacts. To reduce bias all artifacts were blinded to the faculty and randomly assigned to faculty for scoring.

Table 2 Objectives for Engineering Faculty Scoring Session

As a result of this workshop, participants will be able to:	
1	Become familiar with and use the scoring rubric to assess students' evidence of critical thinking in writing.
2	Work in teams to read, assess, score, examine and discuss "benchmark" papers.
3	Practice scoring.
4	Address issues of inter-rater reliability.
5	Contribute to program/department work related to assessment for future improvement.

Table 3 Code of Ethics for Engineering Faculty Scoring Session

1	Only trained scorers will score student writing samples.
2	Scorers will use current materials and apply scoring standards accurately and consistently.
3	Scoring judgments are made using scoring tools (rubric with criteria and performance levels).
4	The university, department or program will maintain documentation that scorers have been appropriately trained.
5	Scorers will not encourage other scores to assign higher or lower scores than are evident to scorer.
6	Scoring will not be compromised by lack of training or inappropriate scoring conditions.

6. Assessing Student Artifacts with the Holistic Engineering Critical Thinking Rubric

Each of the 176 written artifacts from freshman engineering students were independently scored by two engineering faculty. The fifteen engineering faculty were randomly paired for multiple scoring session of six to seven student artifacts, which resulted in a total of 22 faculty pairings for the 176 artifacts. The scores of the two faculty were deemed acceptable if they were either identical or within one point of each other. If there was a two or three point disagreement in the scorings a 3rd faculty scored the artifact. The majority of artifacts (78, 44.3%) were scored by two faculty within one point and 66 artifacts (37.5%) had exact agreement scores by two faculty. Of the 32 artifact scores (18.2%) resolved by a 3rd rater, only two of those artifacts differed by three points. The scores ranged from 1-4 with an average of 2.60.

The consistency of faculty rater scores was assessed using the intraclass correlation coefficient (ICC). Table 4 presents the ICC and significance for each faculty rater pair. The consistency of ratings ranged from 0.94 to –0.412. The majority of the ICCs were greater than 0.4 (59%) and seven (54%) of those were significant at the 0.05 level. The three negative ICCs (14%) reflected a high within-subjects variance for artifacts rated by those faculty pairs.[39,40] The negative ICCs occurred in different faculty pairs.

Table 4 Intraclass Correlation Coefficients for Faculty Rater Pairs

Faculty Rater Pair	ICC
1	0.677*
2	0.36
3	0.414
4	0.519
5	0.6
6	-0.412
7	-0.216
8	0.4
9	0.442
10	-0.333
11	0.32
12	0.581*
13	0.441*
14	0.00
15	0.757*
16	0.727*
17	0.533
18	0.94*
19	0.125
20	0.7*
21	0.095
22	0.00

*p<0.05

7. Future Directions for Critical Thinking Assessment using the Holistic Rubric

The critical thinking rubric was an effective assessment across freshmen student artifacts and between faculty raters. Areas to consider with future rating sessions include:

- continuing to emphasize criterion referenced artifact scoring with the rubric and avoiding norm- referencing based on other artifacts
- reinforcing the importance of scoring the artifact as a whole instead of based on individual components
- using benchmark or anchor samples to illustrate expected performance at different academic levels (freshman to senior)
- monitoring for bias and fatigue during scoring sessions

The next steps in refining the rubric are to continue using the rubric to assess additional student artifacts collected during the longitudinal study, compare critical thinking scores from the rubric with other critical thinking scores, and begin development of benchmark or anchor samples for the scale levels. A second set of written critical thinking artifacts for assessment have been collected from the initial freshman study cohort who are now in their sophomore year. Additionally, another freshman cohort has been consented and written critical thinking artifacts have been collected for assessment. Once the additional critical thinking artifacts are scored, comparison of data within the 1st cohort across academic years and comparison of freshman data across the two cohort groups will provide beginning comparative and trend critical thinking data. Correlating critical thinking holistic rubric scores generated by the engineering faculty with those generated on the identical artifact by other faculty as part of the university-wide general education assessment will provide a measure of convergent validity. Lastly, creating benchmark or anchor samples for the rubric scale levels at each academic level will strengthen the rater training and enhance inter-rater reliability.

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