Enhancing Critical Thinking Across The Undergraduate Experience: An Exemplar From Engineering

Patricia A. Ralston, University of Louisville, USA
Cathy L. Bays, University of Louisville, USA

ABSTRACT

Faculty in a large, urban school of engineering designed a longitudinal study to assess the critical thinking skills of undergraduate students as they progressed through the engineering program. The Paul-Elder critical thinking framework was used to design course assignments and develop a holistic assessment rubric. The curriculum was re-designed to include deliberate teaching of critical thinking and assessment in at least one key course for every student each year of their undergraduate curriculum. The critical thinking scores for seniors using the holistic rubric were significantly higher than their baseline critical thinking scores as freshmen (p = .004). This case-study can serve as an exemplar for other units, departments, or programs to model or replicate.

Keywords: Critical Thinking Assessment; Undergraduate; Engineering; Exemplar

INTRODUCTION

In 2007, the university began implementing a multi-year plan to enhance undergraduate students' critical thinking skills in all undergraduate programs as part of the Southern Association of Colleges and Schools (SACS) regional reaccreditation process. To focus the reaccreditation plan, the university selected Scriven and Paul's (1987) definition that 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 and action*. Faculty, administrators and staff responsible for leading the initiative reviewed several critical thinking models but unanimously agreed to select the Paul-Elder critical thinking framework (Paul and Elder, 2009) to provide intentional and consistent language across undergraduate programs because of the Paul-Elder framework's comprehensiveness, discipline neutral terminology and extensive high quality resources. The Engineering School embraced the process because engineering faculty felt, and research supports that critical thinking is foundational to engineering education and to engineering practice (Alfrey and Cooney, 2009; Rogers, 2006). Although critical thinking and assessment of critical thinking using rubrics have been discussed in the engineering education literature (Berge and Flora, 2010; Goulter et al., 2009; Ralston and Bays, 2010), the studies have primarily related to a single course, not complete curriculum redesign and assessment. Although program assessment of critical thinking has been undertaken in other fields (Bensley and Murtagh, 2012; Cavaliere and Mayer, 2012; McKitrick and Barnes, 2012), the only published discussion of program assessment of critical thinking for engineering was the recent work of Eppes et al (2012). Their work presents an assessment framework for five liberal education outcomes, including critical thinking, in the University of Hartford's engineering and technology programs, but gives results from only a pilot study involving one capstone design course.

This paper presents the first cohort results from a comprehensive curricular redesign and assessment of critical thinking at a large, urban engineering college with 14 ABET (Accreditation Board for Engineering and Technology) accredited programs. In fall 2008, faculty at the Engineering School began a longitudinal, three cohort educational research study to incorporate the Paul-Elder critical thinking framework intentionally and transparently, across the undergraduate engineering curriculum. Faculty developed and implemented a plan for assessing program results that operates as an ongoing feedback loop consisting of implementation, then assessment, followed by revision, then re-assessment for evaluation of critical thinking skills, much as the ongoing Accreditation Board for Engineering and Technology (ABET) assessments function for engineering program curricula. First, the Paul-Elder Framework is briefly reviewed and a short summary of the relationship of critical thinking to ABET outcomes is discussed. Then, the baseline data analysis for the first cohort of students that completed the entire redesigned curriculum that included critical thinking each year of the undergraduate program is explained. Details of the longitudinal study development analysis of the freshman course artifacts (baseline and course critical thinking assignments) and associated faculty scoring sessions for all three cohorts can be found in (2011, Inquiry) which could provide a model for other programs.

PAUL-ELDER CRITICAL THINKING FRAMEWORK

The Paul-Elder (2009) critical thinking framework has a formal structure and is a discipline-neutral schema. Figure 1 depicts the Paul-Elder critical thinking framework. 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.

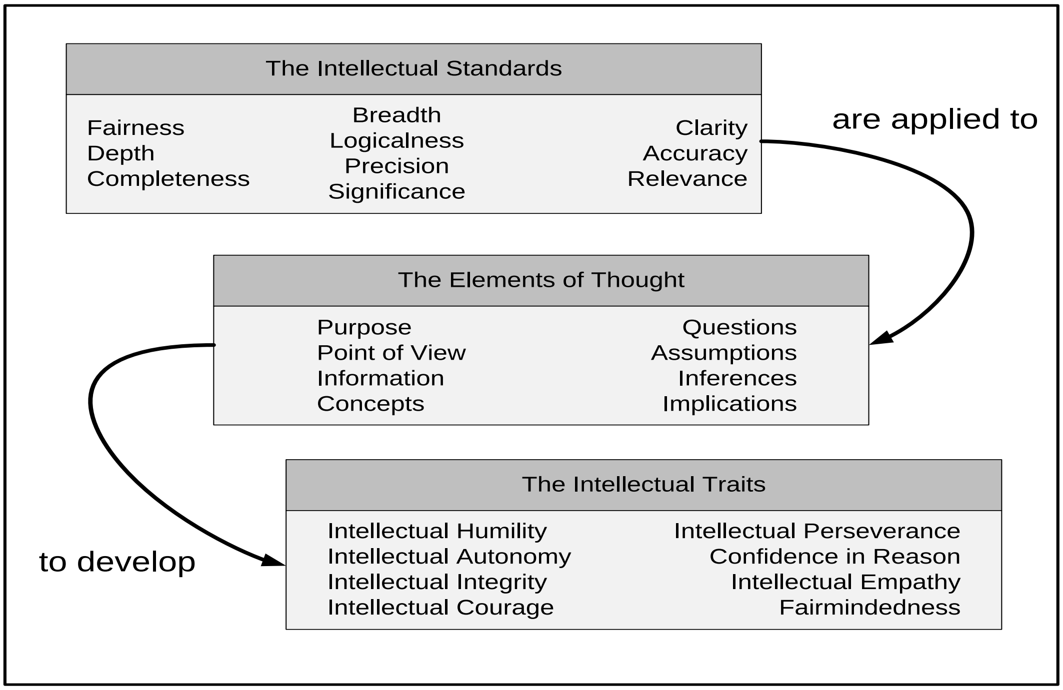

Figure 1: The Paul-Elder Critical Thinking Framework, Adapted from Paul and Elder (2009)

The eight Elements of Thought are the parts or fundamental structures of thought, which are the essential dimensions when all reasoning occurs in all persons at any time. The Elements of Thought work together in a nonlinear interrelationship to shape reasoning and provide a general logic to the use of thought. There is an *intimate overlap among all of the elements by virtue of their interrelationship*. Fundamental to critical thinking is the ability to assess the quality of the reasoning. Assessing critical thinking involves consistently taking apart and examining thinking with respect to the Universal Intellectual Standards of quality. Unlike the complete list of eight Elements of Thought, the ten Universal Intellectual Standards presented in Figure 1 are considered minimal or fundamental intellectual standards within a wider variety from which to choose. The Universal Intellectual Standards are criteria for assessing the quality of reasoning that serve as guides to better reasoning. The Essential Intellectual Traits are developed by consistently applying the Universal Intellectual Standards to the Elements of Thought. The Essential Intellectual Traits are tendencies or commitments towards the trait and not skills or abilities, (Paul and Elder, 2009). 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.

ABET CRITERIA FOR ACCREDITING ENGINEERING PROGRAMS

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 ABET 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 (http://www.abet.org/DisplayTemplates/DocsHandbook.aspx?id=3143).

METHODS

The purpose of this study was to assess the development of critical thinking skills in undergraduate engineering students. The research question was, "How do the critical thinking skills of undergraduate engineering students change as they progress through the engineering program?" The study was a descriptive, longitudinal study of three engineering student cohorts as they progressed through the four year undergraduate program. The study was approved by the university's Institutional Review Board.

PARTICIPANTS

Undergraduate engineering students were eligible to participate in the study if they were at least 18 years of age as freshmen and would complete the undergraduate engineering program in four years. A convenience sample of 187 undergraduate engineering freshmen students consented to participate in the study (51% consent rate). For the sample, the students mean high school grade point average was 3.71 (SD 0.31) and ACT composite score was 28.11 (SD 2.9). The majority of the sample was Caucasian (83%) males (79%).

Forty-nine of the sample (26% of those who consented) completed the undergraduate engineering program in four years and are the unit of analysis for the longitudinal study. The greatest decrease in the study sample occurred from the freshman to sophomore year where 65 of the freshmen subjects continued to the sophomore year (35% of original consent). This initial decrease was primarily due to first year attrition since students often transfer to other majors their first year. The continued decrease in sample size was primarily due to students changing majors within engineering failing to stay in the regular sequence of program courses due to dropping courses, not taking a full load, or other reasons.

DATA COLLECTION

The process started with a core group of committed faculty who recognized that although most all engineering courses required students to think critically, faculty were not specifically teaching students how to think critically. Faculty typically "*demonstrated*" critical thinking as they solved problems or discussed ethical or technical issues, rather than explicitly using a common language and framework to thoroughly discuss the "*analyze and evaluate*" process of critical thinking so clearly articulated in (Nosich, 2012). Engineering faculty developed or revised a critical thinking assignment for a selected course in each year of the undergraduate program. The assignments were authentic assessments embedded within the courses as part of the grading requirements and direct assessments of the students' critical thinking abilities for course specific content. Student responses to the assignments (artifacts) were copied before grading, all identifying information was removed, and a unique study number was placed on the artifacts for tracking across the four-year study time period.

Several faculty members in every department embraced the project to the extent that we are convinced every student was thoroughly exposed to the Paul-Elder critical thinking framework in at least one course per year. The specific critical thinking assignment for a course each year that all engineering students took was:

- *Freshman:* For "Introduction to Engineering" course, a case-study was used to introduce various aspects of engineering before the Paul-Elder critical thinking framework was intentionally discussed in the course. The case study served as the baseline or "pre" assessment.
- *Sophomore:* The "Differential Equations" course's artifact was a one page assignment that required students to answer the question "If you had time to teach only one method to solve differential equations, which method would you pick and why?" Faculty reviewed the Paul-Elder critical thinking framework before this assignment was submitted.
- *Junior:* The artifact collected from third year students was their cooperative internship report summary which asked students to critically reflect on their primary responsibilities. The cooperative internship seminar classes spent time formally reviewing the Paul-Elder critical thinking framework, as well as modeling for students how critical thinking skills could be used in interviewing and in engineering practice.
- *Senior:* Artifacts from fourth year courses from the seven degree-granting departments were written summaries from either capstone design projects or other individual assignments requiring critical analysis. In the fourth year, some faculty teaching courses where artifacts were collected made overt efforts to teach the Paul-Elder critical thinking framework, and others simply provided review materials.

ANALYSIS

No existing critical thinking rubric was found that incorporated the Paul-Elder critical thinking framework for engineering. The engineering faculty decided to construct a four-point, holistic critical thinking rubric based on the Paul-Elder critical thinking framework for use with the research project (Ralston and Bays, 2010). Figure 2 presents the engineering holistic critical thinking rubric.

University of X
X 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 includes 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.

*Based on the Paul-Elder critical thinking framework

Figure 2: Engineering Holistic Critical Thinking Rubric

A total of 15 engineering 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 multi-year length of the research project. Engineering faculty were trained to score the blinded artifacts using the holistic critical thinking rubric. At least two faculty independently scored each artifact. Each faculty rater was given a file with the blinded student artifacts, assignment description, critical thinking rubric, and form to record their scores. If there was greater than a one point discrepancy between the two faculty rater scores, a third faculty scored the artifact. Final critical thinking scores for each artifact were determined by averaging the two or three blinded, independent faculty rater scores. The intraclass correlation coefficient (ICC) was used to assess the consistency of the 42 paired faculty rater scores across the four assessment periods. The ICCs ranged from 0.94 to -0.811. Forty five percent of the ICCs were greater than or equal to 0.4 (n = 19) and 6 (32%) of those were significant at the 0.05 level. The 8 negative ICCs (19%) reflected a high within-subjects variance for artifacts rated by those faculty pairs (Bartko, 1976; Shrout and Fleiss, 1979). The number of negative ICCs occurred in different faculty pairs. The number of artifacts that necessitated a third rater averaged 17% across the four assessment periods.

FINDINGS

A repeated measures ANOVA was used to assess the change in subject's critical thinking scores over time. The assumption of sphericity, relatively equal variances, was evidenced by Mauchly's Test of Sphericity (W = .893, $X^2(5) = 4.715$, $p = 0.452$) so no corrections were applied to the F-ratio computations. The mean critical thinking rubric score for the freshman artifact was 2.599 (SD 0.107), sophomore 2.625 (SD 0.090), junior 2.833 (SD 0.088), and senior 3.152 (SD 0.098). Figure 3 depicts the critical thinking scores for the four assessment points.

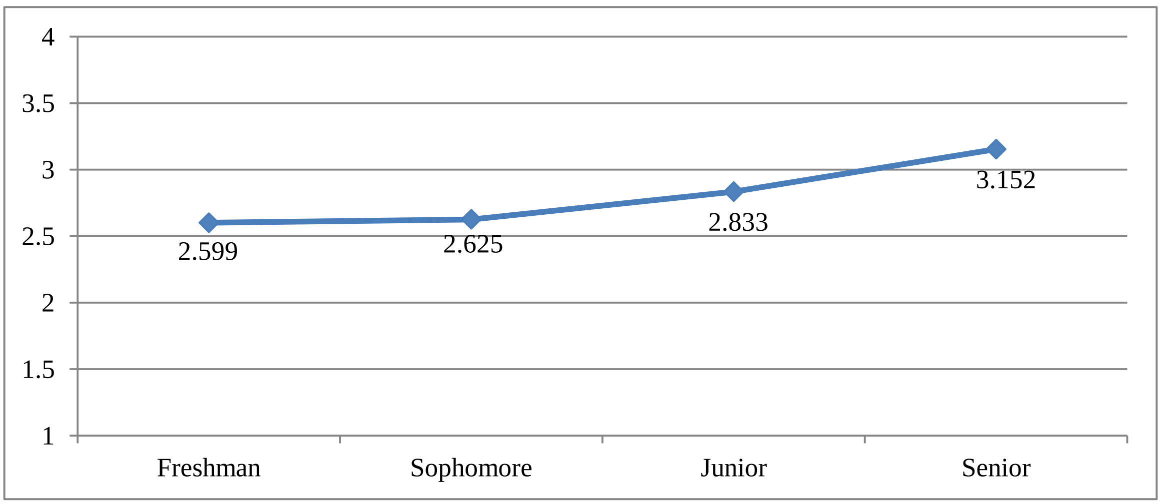

Figure 3: Critical Thinking Rubric Mean Scores

There was a statistically significant increase in critical thinking scores over the four years ($F(3) = 6.693$, $p = .000$). Specifically, the critical thinking score for the senior artifact was significantly higher than the freshman ($p = .004$) and the sophomore ($p = .002$) critical thinking scores. Table 1 reports the Bonferroni comparison for the critical thinking scores.

Table 1: Bonferroni Comparison of Critical Thinking Scores

Comparison	Mean Score Difference	Std. Error	Sig.	95%CI Lower Bound	95%CI Upper Bound
Freshman with Sophomore	.026	.147	1.00	.433	.380
Freshman with Junior	.235	.147	.707	.641	.172
Freshman with Senior	.553	.152	.004	.973	.133
Sophomore with Junior	.208	.113	.435	.521	.105
Sophomore with Senior	.527	.135	.002	.901	.152
Junior with Senior	.318	.140	.169	.706	.069

CONCLUSIONS

Faculty involvement in the creation of critical thinking assignments across the curriculum and assessment of student responses to the critical thinking assignment can strengthen the students' development of critical thinking abilities. The significant increase in the seniors' critical thinking scores from the holistic rubric is consistent with seniors from the same year whose score on the Collegiate Assessment of Academic Proficiency (CAAP) increased 2.4 points from baseline to 68.3, which is especially notable since the national average declined 1.4 points to 60.6 The increase in undergraduate engineering students' critical thinking abilities is an encouraging finding for the engineering profession and public who need engineers who can think critically. An area for refinement is the interrater reliability that can be enhanced by intentional pairing of raters, providing a review of the rating expectations, limiting the rating session to two hours to reduce fatigue, and ensuring each rater pair scores at least 10 artifacts. The primary limitation of the study was the small, convenience sample. Further improvement and refinement will be achieved as engineering faculty strive to increase the number of courses that intentionally focus on critical thinking.

This model for developing assignments and assessing student responses can be duplicated in other disciplines interested in program assessment of critical thinking. Results from the two remaining cohorts will guide further refinement of this engineering school's assessment of students' critical thinking skills. However, these results support that the overt teaching of critical thinking using the Paul-Elder framework has a positive impact on engineering students.

AUTHOR INFORMATION

Patricia Ralston, Ph.D. (U. of Louisville, 1983) is currently Professor and Chair of the Department of Engineering Fundamentals (EF) and also an Associate in the Chemical Engineering Department at the University of Louisville. As Chair of EF, she is responsible for: faculty who teach undergraduate first year engineering courses for the J. B. Speed School of Engineering, the advising of entering freshmen, and the coordination of outreach programs that promote engineering as a profession to elementary, middle, and high school students. She teaches undergraduate engineering mathematics courses and the introduction to Engineering course where she is currently involved in educational research on effective use of Tablet PCs in engineering education and the incorporation of critical thinking in engineering education. Her additional fields of expertise include process modeling, simulation, and process control. E-mail: parals01@louisville.edu

Cathy L. Bays, Ph.D., RN (U. of Cincinnati, 1995) is currently the assessment specialist for the University of Louisville's regional reaccreditation initiative. Prior to the current position she was an Associate Professor and Director of the School of Nursing's undergraduate program. Her areas of expertise and research interest are critical thinking assessment, creative teaching methodologies, and quality of life for stroke survivors. E-mail: cathy.bays@louisville.edu (Corresponding author)

REFERENCES

1. Alfrey, K., and Cooney, E. (2009). Developing a rubric to assess critical thinking in assignments with an open-ended component. Proceedings of the 2009 American Society for Engineering Annual Conference and Exposition, Austin, Texas, AC2009-653.
2. Bartko J.J. (1976). On various intraclass correlation reliability coefficients. *Psychological Bulletin, 83*, 762-765.
3. Bensley, D. & Murtagh, M. (2012). Guidelines for a scientific approach to critical thinking assessment. *Teaching of Psychology, 39*, 5-16.
4. Berge, N. & Flora, J. (2010). Engaging students in critical thinking: An environmental engineering effect. Proceedings of the ASEE National Conference and Exhibition, Louisville, KY, Paper AC 2010-1752.
5. Cavaliere, J. & Mayer, B. (2012). Flooding the zone: A ten-point approach to assessing critical thinking as part of the AACSB accreditation process. *Education, 133*, 361-366.
6. Eppes, T.A., Milanovic, I. & Sweitzer. F. (2012).Towards liberal education assessment in engineering and technology programs. *Journal of College Teaching and Learning, 9*, 171-177.

7. Golter, P., Van Wie, B., Brown, G., Thiessen, D., Yurt, N., & Abdul, B. (2009). Aligning assessment tools with course subject and goals. Proceedings of the ASEE National Conference and Exhibition, Austin, TX, Paper AC 2009-2320.
8. McKitrick, S. & Barnes, S. (2012). Assessment of critical thinking: An evolutionary approach. *Journal of Assessment and Institutional Effectiveness, 2*, 1-29.
9. Nosich, G.M. (2012). *Learning to think things through: A guide to critical thinking across the curriculum*. Upper Saddle River, NJ: Pearson Prentice Hall.
10. Paul, R. & Elder, L. (2009). C*ritical thinking: Concepts & tools.* Dillon Beach, CA: The Foundation for Critical Thinking.
11. Ralston, P. & Bays, C. (2010). Refining a critical thinking rubric for engineering. Proceedings of the 117th ASEE Annual Conference and Exhibition, Louisville, KY, AC 2010-1518.
12. Rogers, G. (2006). Rubrics: What are they good for anyway? Part I *Community Matters*, September, 3.
13. Scriven, M. & Paul, R. (1987). Defining Critical Thinking. Retrieved December from: http://www.criticalthinking.org/pages/defining-critical-thinking/410
14. Shrout P.E. and Fleiss, J.L. (1979). Intraclass correlations: Uses in assessing rater reliability. *Psychological Bulletin, 86*, 420-428.

NOTES