AC 2012-3257: CRITICAL THINKING IN ELECTRICAL AND COMPUTER ENGINEERING

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Critical Thinking in Electrical and Computer Engineering

Abstract

As part of the Speed School of Engineering's response to a SACS' mandated University wide quality enhancement program (QEP) all incoming freshman are given explicit and implicit instruction in critical thinking in *Introduction to Engineering* (ENGR 100) and other engineering fundamentals courses. In *Introduction to Engineering* students are taught explicitly about critical thinking by using the Paul-Elder framework of critical thinking to define and operationalize critical thinking. The instruction is followed by explicit critical thinking exercises. The critical thinking instruction in ENGR 100 and engineering fundamentals courses prepare students to embrace more elaborate, discipline specific, critical thinking required of them in future courses and begins associating critical thinking with the practice and profession of engineering. Critical thinking education continues beyond fundamentals courses as critical thinking instruction and assessment moves into specific departments.

In the Electrical and Computer Engineering program, at the sophomore level, the network analysis course has been selected for critical thinking emphasis. Students will be encouraged to use the critical thinking skills which were developed during their engineering fundamentals courses, to analyze requirements and constraints which would apply in real-world design projects using the material covered in this course. At the junior level, similar use of critical thinking will be applied in an introductory MATLAB course. At the senior level, critical thinking skills will again be strengthened and assessed in the capstone design course and the professional issues and current topics seminar. The latter course emphasizes understanding of professional ethics and current topics in electrical and computer engineering. Initial data indicates statistically significant improvement in critical thinking skills in ECE students who have been through this sequence.

1 Introduction

The Southern Association of Colleges and Schools (SACS) now requires all accredited schools to design and implement a quality enhancement program. In 2007 the University of Louisville adopted as its quality enhancement program (QEP) the requirement that all schools within the University, including the school of engineering, develop and implement an ongoing and school wide program to "improving the critical thinking skills of undergraduate students and to more effectively prepare them to contribute to society"[1]. This program has been named ideas to action (i2a). The lack of explicit critical thinking outcomes and content in course syllabi as well as results by Cooney et al.[2] suggest that engineering students can benefit from improved critical thinking instruction. Cooney et al.[2] present survey results that showed a disconnect between the amount of critical thinking experience engineering and technology faculty at IUPUI believed they were providing to students and the amount of critical thinking experience students perceived they were receiving. Furthermore, critical thinking supports various ABET program outcomes. Specifically, critical thinking skills support engineering students developing the "broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context."[3] Critical thinking also supports the ABET program outcome "a recognition of the need for, and ability to engage in, life-long learning"[3]. And finally critical thinking is an essential component of "the ability to identify, formulate, and solve engineering problems"[3]. Other schools have reached similar conclusions[4].

Section two describes the Speed School of Engineering's response to the i2a initiative, and briefly describes some of the implementation of that response in fundamental courses common to all engineering students. Section three discusses the Electrical and Computer Engineering (ECE) department's plans to emphasize critical thinking in the sophomore courses *Network Analysis 1* and *Logic Design*, the junior level course *Embedded System*, and in the senior courses *Capstone Design* and *Professional Issues and Current Topics Seminar*. Section four discusses some preliminary critical thinking assessment done in the *Professional Issues and Current Topics Seminar* course. Concluding remarks and future plans are discussed in section five

2 Critical thinking at the Speed School of Engineering

In response to the University's i2a initiative, the Speed School of engineering has developed a multi-leveled critical thinking program that begins with the school's freshman program: *Introduction to Engineering*, and goes on to include sophomore, junior, and senior courses, co-op reports, and undergraduate engineering capstone projects. A graphical representation of the current plan is shown in figure 1. At points in the curriculum, critical thinking is explicitly incorporated into specific courses through instruction, activities and assignments. More advanced and discipline specific critical thinking is characteristic of the upper level courses and capstone projects. General critical thinking, focused on ensuring students are able to clearly define critical thinking, recognize critical thinking, and applying critical thinking to simpler and well defined problems is the focus in lower level courses. While there are specific courses targeted for critical thinking instruction and assessment, it is the intention that most courses become more intentional in their treatment of critical thinking. A primary way in which this will happen is through the use of a common language for critical thinking. To facilitate this, the Paul-Elder framework for critical thinking has been adopted as the model for critical thinking. Instructors can use the framework in their lecture, in their assignments, and in their assessments. In fact a holistic rubric for critical thinking, based on the Paul-Elder framework, has been developed and is given in appendix A. An instructor's incorporation of the Paul-Elder framework as a common language will allow students to readily recognize critical thinking, without explicit mention on the part of the instructor.

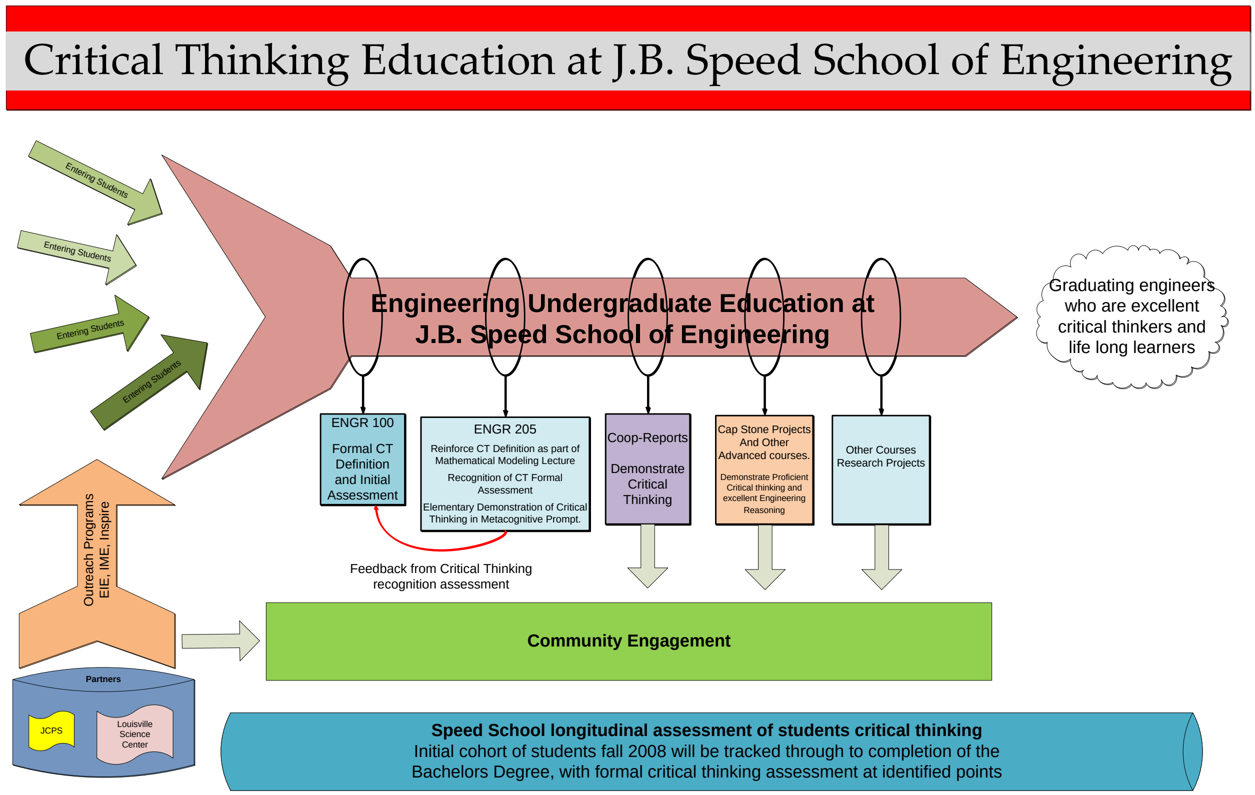

Figure 1. Speed School of Engineering critical thinking education plan.

2.1 The Paul-Elder framework of critical thinking

The Paul-Elder framework decomposes critical thinking into Standards, Elements, and Intellectual Traits, and imposes the following relationship on that decomposition: the standards are applied to the elements as we learn to develop intellectual traits. The purpose of the framework is to aide in the analysis and evaluation of thought and to provide a common vocabulary for critical thinking. A benefit of this framework is that it is a discipline neutral, general framework for critical thinking. The framework is shown in figure 2.

For students and instructors the framework provides a common framework for defining and operationalizing critical thinking by defining eight elements of thought which capture how critical thinking examines, analyzes, and reflects on intellectual work. These eight elements lead to eight categories of questions present, to some degree, in all critical thinking: (1) what is the purpose? (2) what is the point of view? (3) what are the assumptions? (4) what are the implications? (5) what information is needed? (6) what inferences are being made? (7) what is the most fundamental concept?, and (8) what is the question that is being answered? The intellectual standards describe the criteria used to evaluate the quality of the critical thinking. For example: *the thinking has a clear purpose or makes relevant assumptions*. The intellectual traits are the characteristics associated with a mature critical thinker and are developed by individuals over time. Hopefully students will develop and exhibit these traits as they proceed through the curriculum. For more information on the Paul-Elder framework for critical thinking the reader is referred to the The Miniature Guide to Critical Thinking Concepts & Tools, by Richard Paul and Linda Elder[5] and the The Thinker's Guide to Engineering Reasoning, by Richard Paul, R. Niewoehner, and Linda Elder[6]. The Speed School of Engineering is working towards making these guides universally available to its students.

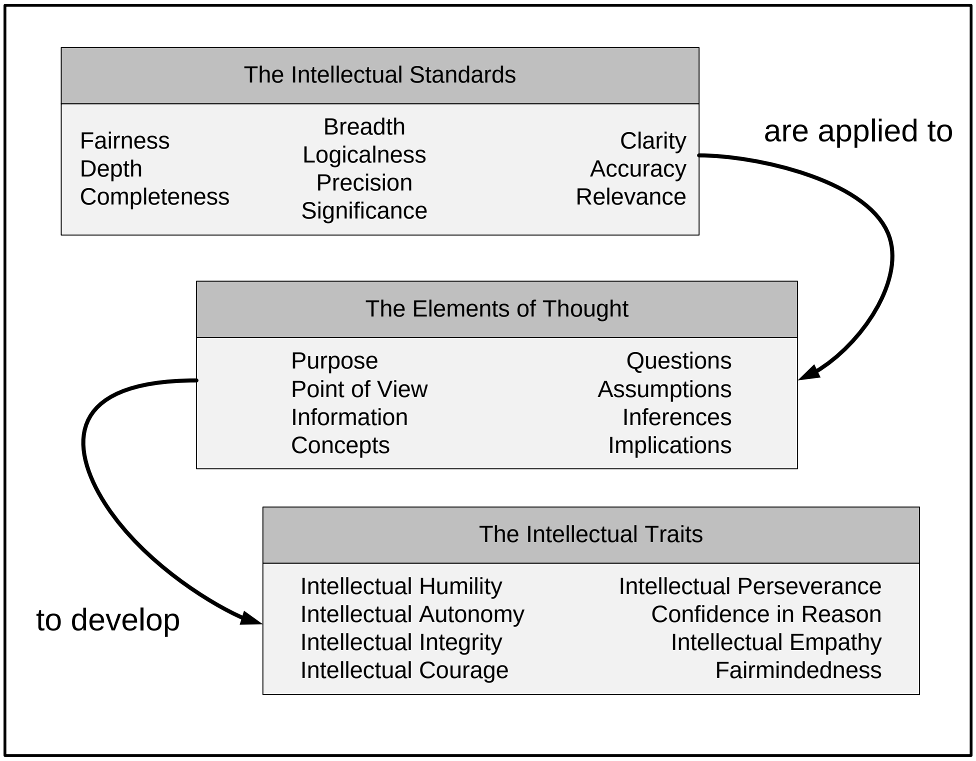

Figure 2. The Paul-Elder framework for critical thinking, adapted from[5].

2.2 Critical thinking instruction in engineering fundamentals courses

Incoming engineering students may have misconceptions about critical thinking, may find it difficult to define critical thinking, and their critical thinking skills are likely to be at a variety of different levels. To address this, critical thinking is made an explicit component in *Introduction to Engineering*, *Differential Equations for Engineers*, and *Cooperative Education Seminar*. These courses are common to all engineering students, and should be completed by the end of the fall semester of the second year. The critical thinking instruction in these courses includes explicit instruction of the Paul-Elder framework, explicit and overt modeling of critical thinking, and specific critical thinking activities.

A review by Cooney and colleagues[2] of recent educational literature identified two distinct themes when it came to developing critical thinking skills in engineering and technology students. Those two themes are writing for reflection and problem-based learning. Writing for reflection promotes critical thinking by having students digest given information, analyze the content and the thinking, think about their own thinking, and then articulate their thoughts and/or value judgments. Problem solving is a central component in engineering and technology, and problem-based learning is a natural extension of the problem solving common in engineering, and creates opportunities for students to "do" critical thinking. These two approaches have served as inspiration for the development of critical thinking instruction in fundamentals course, though other more direct approaches are also used.

In *Introduction to Engineering*, students are given explicit instruction on the Paul-Elder framework during a traditional lecture based class meeting. The Elements and Standards of critical thought, shown in figure 2, are presented, explained and exemplified to the class. Then, following the lecture, students go to their respective breakout rooms (about 30 students per room). During the breakout part of the class, there is a review of The Elements and The Standards. Then students work individually on four or five problems that require critical thinking (including two questions that were introduced during the lecture portion of the class). As a conclusion, students are asked to discuss which elements of critical thought were important in solving the problems, an oral form of writing for reflection.

Critical thinking instruction is also incorporated into the case studies that are used in the *Introduction to Engineering* course. In their presentation of case study material, instructors model critical thinking to students. They use the Elements and Standards from the Paul-Elder framework (without making explicit reference to the framework) to help students fortify their understanding of critical thinking and become aware of the fundamental relationship between critical thinking and engineering. During case studies activities, students are provided an opportunity to evaluate both their own and other's thinking to determine if it incorporates the Elements and Standards of critical thought. For example, students are advised to review their papers to ensure they contain the elements of critical thought and that all information, analysis and conclusions are presented clearly and logically and that all questions are completely answered. When presenting their own case study analysis, instructors use The Elements and The Standards of Thought from the Paul-Elder framework to emphasize the parts of their analysis that exemplify critical thinking. Finally, students are encouraged to compare their critical thinking to the critical thinking of an engineer or group of engineers whose thinking they have become familiar with during the case study. The case studies thereby reinforce the implicit critical thinking elements of the course; giving the students a chance to see and implement critical thinking as they work on the case study assignments and activities. A more detailed description of the critical thinking instruction in Introduction to Engineering is provided by Lewis, Hieb and Wheatley[7].

Differential Equations for Engineers is typically taken in the fall of the second year. It is a required course for all engineering majors. Beginning in the fall of 2009 this course began including specific critical thinking activities. The Paul-Elder framework is incorporated into the course material on mathematical modeling. The Paul-Elder framework provides an excellent context for the activity and evaluation of developing mathematical models, and The Elements and The Standards of Thought are found throughout the text's discussion of mathematical modeling. During lectures where the differential equations for spring mass systems, electrical circuits and mixing problems are developed, the language of the Paul-Elder framework is used to highlight the critical thinking present in the development of the models. Finally, at the end of the course, students are asked to do a critical thinking writing for reflection activity related to methods for solving differential equations. This writing for reflection artifact is used as part of an assessment of the progress individual engineering students are making in developing good critical thinking skills.

The *Cooperative Education Seminar* discusses the policies and procedures for cooperative education and provides students with instruction about job search, interviewing skills, resume preparation, and gives guidelines for the co-op report. In the co-op report, students report back on their co-op experience. During the summer of 2008, cooperative education staff and faculty created and administered a survey to assess the effectiveness of the cooperative experience, with a primary emphasis on critical thinking expectations for the final internship report. Based on the survey results, a session on critical thinking was added to the seminar. The session relates critical thinking, using the Paul-Elder framework, to the co-op experience. The report format for the co-op reports has been altered to require students to explain how they used critical thinking during their internship (writing for reflection).

At this point, critical thinking instruction and assessment move into specific departments. Each department is working on selecting upper level courses in which to infuse critical thinking, and assuring that critical thinking is explicitly a part of the assessment of capstone projects.

3 Critical thinking in Electrical and Computer Engineering

In planning how the Department of Electrical and Computer Engineering (ECE) would meet the requirements of the University-wide, quality enhancement program (QEP), there was unanimous agreement that critical thinking is an important requirement to be successful within the electrical engineering profession. In an effort to help students become better critical thinkers and appreciate the importance of its practice throughout their education and careers, critical thinking and engineering reasoning was implemented in several key courses throughout the ECE curriculum. At the current time critical thinking instruction is formally incorporated into one sophomore level course, one junior level course, and two senior level courses, while informal critical thinking instruction is a part of most of the remaining courses in the undergraduate ECE curriculum. At present, the assessment of this activity has not been incorporated into the broader ABET assessment activities of the ECE Dept. Critical thinking obviously impacts many of the required eleven program outcomes, and could be incorporated into the assessment of one or more of them.

At the sophomore level, the ECE 220 *Network Analysis I* course was selected for critical thinking emphasis. Co-author Welch introduced critical thinking methods into ECE 220 over three semesters with promising results in better student performance. This course builds the foundation for more advanced circuit analysis, so creating an environment where students think critically about the material should lead to deeper understanding of circuits' concepts as students progress through the discipline. Therefore, ECE 220 is a key course in the curriculum for the ECE department to implement critical thinking (CT) techniques and evaluate the outcomes to guide best practices in the future.

The introduction of CT into ECE 220 started with one exercise in the spring of 2010 and gradually built in more CT exercises each semester. Each semester, lesson 4 (Node Voltage Method for solving electrical circuits) and lesson 5 (Mesh Current Method for solving electrical circuits) have been the focus for CT exercises. These lessons are similar enough that introducing a new learning method in one could be used to compare to the other, as opposed to comparing dissimilar topics. In the Spring 2010 semester, the students completed one SEE-I [8] on lesson 5. A SEE-I asks students to briefly **State** the definition of a topic (e.g., "The Mesh Current Method is..."), **Elaborate** on that definition (e.g., "To elaborate,…" or "In other words, the Mesh Current Method is..."), give an **Example** of the topic (e.g., "For example, in the circuit below, the mesh currents are..."), and **Illustrate** how the topic is analogous to a related concept (e.g., "Another way to think of the Mesh Current Method is..."). Students worked through the SEE-I on the topic of "the Mesh Current Method" with their homework partner at the end of the lecture instruction for the lesson. The SEE-I exercises were subsequently discussed in class.

The SEE-I provides a way to analyze what foundational information students are using to base their equations to represent a circuit. For example, in Spring 2010, only a few student groups mentioned in their Elaboration on Mesh Current "resistor in a shared branch between meshes," but defining whether an electrical component like a resistor is shared or not between meshes is a pivotal piece of evidence with which to formulate the equation to represent the circuit. Without CT exercises like the SEE-I, it can be difficult for the instructor to tease out from an incorrect equation what concept or underlying information the students are misunderstanding or not identifying as significant. Significance is one of the Universal Intellectual Standards in the Paul-Elder framework of CT (Paul and Elder, 2009); therefore, incorporating more exercises that ask students to analyze a problem through CT; such as identifying the *significant* factors of a problem, delineating the *logic* of their solution method, and evaluating the *accuracy* of their answer; will highlight their misconceptions which will direct the instruction and presumably increase their understanding.

A second SEE-I for lesson 4 was introduced in Fall 2010, and the lesson 5 SEE-I was kept as before. Standard quizzes were given to check student mastery of the circuits concepts covered in these lessons. The quiz averages on each of these lessons increased significantly over the Spring 2010 semester, from 61.73% to 82.73% for lesson 4 (p = 0.0003, significant) and from 69.73% to 86.14% for lesson 5 (p = 0.0004, significant). The SEE-I was kept for the Fall 2011 semester, and quiz scores remained high (see Table 1). When comparing quiz scores between Fall 2010 and Fall 2011, for both lesson 4 and lesson 5, scores were statistically the same (p = 0.461and p = 0.650, respectively).

Table 1 - Quiz Averages from Introductory Circuits Course

Semester	N	Lesson 4 Quiz Average (%)	Lesson 5 Quiz Average (%)
Spring 2010	15	61.73	69.73
Fall 2010	22	82.73	86.14
Fall 2011	32	78.59	87.81

For the most-recent semester, a CT focus early-on in the semester was added. During the first week of this class students viewed a video taken on graduation day at MIT's campus (Private Universe Project, 1989). In the video recent engineering graduates were asked if they thought they could turn on a light bulb using a battery and wire. The scene plays out that although all students proclaimed confidently that they could do this task, ultimately they could not turn the bulb on, and furthermore, they could not explain why their bulb-wire-battery assemblies did not work. After the video co-author Welch asked students in ECE 220 what skills the MIT engineering graduates may be lacking that would have improved their performance in the light bulb task. They were given a list of skills that graduates should acquire on their way to earning a degree. The poll results show students believed better critical-thinking skills (most-popular choice) and application skills (second-most-popular choice) would have been the most-beneficial for the students in the video.

For lesson two, students were asked to consider the *point of view*, one of the Elements of Thought[5], of a manufacturer of resistors used in electrical devices. One of the homework problems asked students to design a specific configuration of an amount of resistance, price the cost of their design with an online supplier, and then use critical thinking to answer why a manufacturer would stock some values of resistors but not every imaginable value. All students were able to connect that since resistors can be combined to provide different amounts of resistance, stocking a few general values that can be used in different combinations in many devices is more efficient than stocking a vast variety of specific values that have more limited applicability. Students unanimously understood that manufacturers must deal with inventory constraints and therefore design engineers must deal with cost constraints related to the availability of components (i.e., a secondary focus of the course), which are important concepts of how engineering design relates to factors beyond the electrical functions of a circuit (i.e., the main focus of the course).

At the junior level, critical thinking is taught and evaluated in the class *ECE 322: Introduction to ECE Computing Tools,* which focuses on teaching the mathematical tool, *MATLAB*™. The approach to teaching critical thinking skills used in this course is to provide an abbreviated review, using the same language and pedagogy used in previous semesters, at the time that *function* calls are covered in the course. Then homework assignments are given that require that a help file be written that describe the purpose of any function they write. The students are specifically told not to simply echo the sequence of computational steps required to carry out the function, but to describe the **Purpose** of the function call. The help files are to be written from a **Point of View** of a person who is not taking the course, and thus has no knowledge of the homework assignment.

For example, in the summer 2011 semester, the students were asked to create a function in Matlab that will output a spectrogram (2-D plot of a Fourier Transform versus time) when input a song filename, and they were required to include a help file, consisting of the following items: (a) Title, (b) Usage syntax, (c) General description of the function, including expected output, (d) Detailed description of the function (including mathematical basis), and (e) Examples of usage. The Paul-Elder standards of **Clarity** and **Accuracy** are present in all portions of the help file. **Precision** and **Completeness** are present in parts b, d, and e. **Significance** is present in parts c and e. **Breadth** and **Depth** are present in parts c and d, as the description must have sufficient depth to permit a thorough understanding of the function, and also contain enough breadth that a user could potentially see how the function could be applicable for other people to solve their own problems.

At the senior level, critical thinking skills will again be strengthened and assessed in the ECE 599 *Capstone Design Course* and the ECE 496 *Professional Issues and Current Topics Seminar*. The latter course emphasizes understanding of professional ethics and current topics in electrical and computer engineering. ECE 496 is of particular interest because it is in many ways the ideal place to perform an overall assessment of the critical thinking skills of electrical and computer engineering undergraduates. Some additional detail about the critical thinking instruction and assessment in this course are presented in the next section.

4 Preliminary Experience in Critical Thinking Assessment in ECE 496

Critical thinking instruction has been incorporated into the course body of ECE 496 *Professional Issues and Current Topics Seminar* for the past two years. Two of the authors who participated in the Faculty Learning Community on i2a Critical Thinking in 2008 and 2009 have taught the class during recent semesters.

This class is an ideal locus for an assessment of critical thinking skills of seniors in the electrical and computer engineering program. All ECE seniors are required to take the course and students are not permitted to take it until they have reached senior (fourth year) status. The course material lends itself well to further practice of critical thinking by students, as they are asked to read quite a bit about current topics in electrical and computer engineering from *IEEE Spectrum* and other sources, and produce a paper on a current electrical or computer technology of their choice. This requires critical reading, evaluation of sources, evaluation of possible biases or other hidden agendas, and the ability to formulate and support their conclusions in a concise and cogent form. Likewise they are asked to investigate an ethical case study, where failure to observe one or more of the precepts of the ethical practice resulted in a catastrophe. Again careful reading and reasoning skills are required.

Each class section during this past year has had review of critical thinking methodologies using The Miniature Guide to Critical Thinking Concepts & Tools, by Richard Paul and Linda Elder[5] as well as in class activities, and a writing assignment. The writing assignment required students to identify and analyze the major themes and soundness of reasoning using the elements of thought from the Paul-Elder framework, including purpose, question, information, concepts, assumptions, inferences, point of view and implications. The writing assignment was scored on the four point critical thinking rubric (Appendix A) and also on a six point writing rubric, emphasizing writing mechanics. Table 2 below summarizes the scores of students who took the class in the summer and fall of 2011. All these students had previously been exposed to critical thinking concepts.

These results were compared to a group of 23 student papers from ECE 496 classes written during the 2009 calendar year. These papers were graded using the same critical thinking and writing rubrics. The mean of the critical thinking scores was 3.00 and the mean of the writing scores was 4.41 for this group of student papers.

Table 2 – Critical Thinking and Writing Scores in ECE 496 in 2011

Section	CT - mean	CT – Std Dev	WR - Mean	WR= Std Dev
Summer 2011 N=6	3.67	__	4.75	__
Fall 2011 N=15	3.53	__	4.73	__
Combined N=21	3.57	0.531	4.74	0.562

The critical thinking scores for the students in the 2011 sections were statistically significantly better than the critical thinking scores of the 2009 cohort (p=.003), yielding support to our observation of better critical thinking abilities for the students who have had systematic exposure to critical thinking instruction throughout their engineering studies, from freshman to senior years. Equally encouraging was the increase in writing scores, which were also significantly better than the writing scores of the 2009 students (p=.132). Written communications ability has been long-standing area of concern for engineering students, and it is encouraging to see this improved performance in a group of electrical and computer engineering seniors!

5 Conclusions

Most engineering professors think that they inherently teach logical thought and critical reasoning to their students. Certainly careful, logical reasoning is one of the hallmarks of our profession. Students who can memorize formulas and crank out numerical problems on our in-class examinations often lack the skills to carefully analyze a problem, identify the key requirements and constraints in real world problems. The University of Louisville is currently engaged in a multi-year experiment to see if we can enhance the critical thinking skills of students and improve their abilities to apply what they learn to real world problems.

The results, both anecdotal and quantitative, from the efforts to date have led the authors to conclude that continuing to adopt CT techniques within the instruction for existing engineering classes will be beneficial both from an instructor's perspective, to provide insight into areas of misunderstanding, and for the student's perspective, to provide them with opportunities to re-examine and deepen their understanding of the material. This paper presents a snapshot of this endeavor as we attempt to apply this new approach to the education of electrical and computer engineering students. It is clearly a work in progress, but initial results are promising.

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Appendix A

University of Louisville
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 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.