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Developing a Methodology for Teaching and Evaluating Critical Thinking Skills in First-Year Engineering Students*

LYNNETTE M. MICHALUK
Center for Excellence in STEM Education, West Virginia University, Morgantown, WV 26506, USA.
E-mail: lynnette.michaluk@mail.wvu.edu

JON MARTENS
Department of Education, Oklahoma State University, Stillwater, OK 74074, USA. E-mail: jon.martens@okstate.edu

REBECCA L. DAMRON
English Department, Oklahoma State University, Stillwater, OK 74074, USA. E-mail: rebecca.damron@okstate.edu

KAREN A. HIGH
College of Engineering and Science, Clemson University, Clemson, SC, 29634, USA. E-mail: khigh@clemson.edu

Many program outcomes required by ABET 2000 criteria require that students learn critical thinking and communication skills as part of the engineering curriculum. In this study, we attempted to improve forty-nine first year undergraduate engineering students' critical thinking skills through two assignments based on the Paul-Elder model of critical thinking, which incorporates characteristics of eight elements of thought of critical thinking and has been contextualized specifically for use in engineering. Two methods were employed: problem-based learning and writing for reflectivity. Students first worked in teams to solve two engineering problems, and then each individual student wrote first and final report drafts for each of the problem solving tasks. Writing fellows provided structured feedback to students on each of their first draft reports based on one of two grading rubrics used to assess reports. Over the course of the semester, students showed improvement in overall critical thinking skills and in some, but not all, of the eight elements of critical thinking according to both grading rubrics. Based on these results, we offer suggestions for the teaching of critical thinking skills to undergraduates in engineering and a call for future empirical research.

Keywords: critical thinking in engineering; writing fellows; problem-based learning; Paul-Elder model of critical thinking; ABET 2000

1. Introduction

In 2000, the Accreditation Board for Engineering and Technology (ABET) revised accreditation criteria to include new program assessments for eleven outcomes that all require critical thinking skills [1, 2]. In the years prior to revised ABET criteria, engineering education had emphasized the development of technical knowledge in science and math. Thus graduates had strong technical skills, but their problem-solving skills were limited at best [3–7, 8]. New criteria were developed in response to employers' dissatisfaction with engineering graduates' perceived lack of knowledge and skills needed in an increasingly global profession where change is the rule, not the exception. Shuman et al. divide several of the required skills into two categories [9]. They refer to communication, teamwork, and the ability to recognize and to resolve ethical problems as "process" skills because each of these can be taught as a process. Understanding the impact of global and societal issues, knowledge of contemporary issues, and the ability to engage in life-long learning are categorized as "awareness" skills, primarily because students learn how to become aware of the importance of each and how to incorporate them in problem-solving pursuits.

For the engineering educator, implementing and integrating these two categories into professional, institutional, and pedagogical goals is complex and becomes more so when working with first-year (FY) students. First-year students often are not knowledgeable or experienced in problem-posing tasks, and as these tasks increase in complexity, so too does the difficulty in thinking and writing about them. It is also well-documented that undergraduate students lack critical thinking skills [4, 6, 7, 10]. The question then arises as to how to help students become competent in ABET 2000 program outcomes as they transition to writing and thinking critically in a new academic community [1, 11].

Various researchers have explored critical thinking in the engineering classroom [4, 12, 13]. Claris and Riley [12] suggest that engineering students must ask questions, and more importantly, they must ask *why* questions *about* engineering in order to become the kind of critical thinkers required by ABET 2000 outcomes [1]. Currently, empirical and anecdotal research shows that two methods are effective in teaching critical thinking skills in the

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engineering classroom: problem-based learning and writing for reflection [13–16]. According to Claris and Riley, reflectivity is necessary for critical thinking to develop [12]. Based on these premises, we developed problem-based learning projects that incorporated reflective writing based on the Paul-Elder Critical Thinking Model [17], which has been contextualized for engineers. Writing fellows provided structured feedback to students on first drafts of reports. Utilizing this approach, we hoped to teach critical thinking skills that would also theoretically encompass ABET 2000 program outcomes a–k [1].

2. Literature review

2.1 Critical thinking in engineering

Employers believe that recent graduates lack critical thinking skills [3–5, 7, 18]. Papadopoulas et al. determined that engineering course content emphasizes explicit content, while the development of analytical technique is lacking [6]. For example, in their study, students often did not have the necessary skills to give both the correct answer *and* the correct reasoning for their answers to mechanical engineering homework problems. As ABET 2000 program outcomes now require, this disconnect between explicit information and the ability to think critically about problems is being addressed in various ways. These include incorporating critical thinking assignments, activities, lectures, and written reports into engineering curricula as well as offering entire courses in effective thinking [10, 14, 19]. More empirical research is needed to determine the effectiveness of some of these methods, but current research supports the success of two methods in teaching critical thinking skills: problem-based learning and writing for reflection [4, 22, 23].

2.2 Critical thinking and problem solving

Problem-based learning provides students with necessary opportunities to practice critical thinking; in addition, problem-based learning has consistently been shown to be effective in teaching critical thinking skills [4, 18, 20, 21, 24, 25]. Problem-based learning is inductive in that the problem is given to students *before* they have the knowledge necessary to solve it [25]. However, the philosophy of critical thinking must be part of the course curricula and must be incorporated into the design, implementation, and evaluation of the project to promote thinking beyond the surface level of a problem [26]. Acquiring the knowledge necessary to solve the problem is part of the problem-solving process. To solve the problem, students must ask questions, formulate hypotheses, and gather information through modeling, experimentation, literature searches, and consulting experts before arriving at a viable solution. In addition, students often work together in teams (as they will in their careers) on an open-ended problem, often with real-world constraints such as time limitations, limited resources, or interruptions in the problem-solving process. Student teams work together to determine what information is needed to solve the problem, collect the necessary information, and then discuss the collected information, suggest and assess potential solutions, and agree upon and present the best possible solution to the problem [2, 14].

2.3 Critical thinking and writing

The link between the development of critical thinking and writing has been explored in both empirical and anecdotal research, and most authors agree that critical thinking and writing are so closely related as to be part of the same process [15, 16, 27–29, 30]. Bean claims that writing is not just the product of critical thinking, but also a process of critical thinking, while Wheeler and McDonald state that writing contributes to both the development and the use of critical thinking skills [29, 31]. Other authors agree that critical thinking skills are enhanced by reflective writing [2, 13, 15, 23, 32, 33]. How does writing for reflection build critical thinking skills? According to Cooney et al., students are challenged to make and then to articulate value judgments about data and information, problems, and potential solutions when writing for reflection [13]. They add that when used systematically, the writing process can be used to support and develop problem-solving skills. Students develop thinking processes that help them critically examine issues and ideas in their writing that are also applicable when solving technical problems. In both cases, a critical thinker will first contextualize the problem to identify elements that define its boundaries; gather necessary information; develop perspectives about the problem based on the information; consider several possible alternative solutions prior to identifying the most reasonable solution based on the context; and examine the underlying assumptions of the proposed solution. In this manner, helping students to develop the critical thought processes necessary for well-reasoned argument in writing also provides them with problem-solving tools necessary for success in engineering [13].

2.4 Writing fellows

Many engineering departments now have in-house writing fellows [34], and a review of the literature shows that writing fellows are beneficial in improving the writing skills of students [34–41]. Structured feedback from writing fellows and/or instructors has been shown to be particularly effective in improving students' writing skills [16, 34, 41–46]. Several studies employing the use of structured feedback from writing fellows have shown that students who received feedback from writing fellows have higher scores on written work than those who don't [36, 43–45]. Feedback must be instructional, specific, and structured to be effective in improving content of student papers: the writing fellow should *not* be editing and revising student's papers, instead, they must provide instruction in *how* to write to the student [2, 4, 42]. While editing by writing fellows or others can certainly produce higher scores on written work, ultimately the goal is to teach students to become better, more reflective, writers. As result of these improvements, students should achieve higher scores for written work. The least effective feedback is given when the instructor simply directs students to exchange papers for editing; most effective is to provide reviewers with a detailed checklist or rubric of areas to be addressed, including content, for assessing first drafts [42]. Another benefit to the revision of students' first drafts by writing fellows or other reviewers is that the review process significantly cuts down on grading time of final drafts for the instructor, assuming that students receive adequate feedback on first drafts [42].

2.5 Critical thinking model

In the current study, we applied the Paul-Elder critical thinking model, which has been contextualized for engineers [17]. According to this model, "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 . . . It entails the examination of those structures or elements of thought implicit in all reasoning: purpose, problem, or question-at-issue; assumptions; concepts; empirical grounding; reasoning leading to conclusions; implications and consequences; objections from alternative viewpoints; and frame of reference" [17].

The Paul model includes three major components of critical thinking, which are in turn divided further. The Intellectual Standards describe the criteria for evaluating the quality of critical thinking and include *clarity*, *accuracy*, *relevance*, *logic*, *breadth*, *precision*, *significance*, *completeness*, *fairness*, *and depth*. These intellectual standards are then applied to the Elements of Thought which summarize how critical thinking is used to examine, analyze, and reflect on intellectual work and include *purposes*, *questions*, *points of view*, *information*, *inferences*, *concepts*, *implications*, and *assumptions*. Finally, as one becomes practiced in applying the intellectual standards to the eight elements of thought, one develops the Intellectual Traits that are characteristically associated with being a mature critical thinker, including *humility*, *autonomy*, *integrity*, *courage*, *perseverance*, *confidence in reason*, *empathy* and *fair-mindedness*; see Fig. 1 [14, 17, 21]. The model provides a useful and concise framework for defining and operationalizing critical thinking for students and instructors [14, 21].

Using the Paul-Elder model as a guide, the goal is to aid in the development of the Intellectual Traits of the thinker through the application of the Intellectual Standards to the evaluation of the Elements of Thought [2, 21]. For additional information about the Paul-Elder framework for critical thinking refer to The Miniature Guide to Critical Thinking Concepts and Tools, by Richard Paul and Linda Elder [46] and The Thinker's Guide to Engineering Reasoning, by Richard Paul and Linda Elder [17]. While the Paul-Elder model has been adopted for use in various contexts, empirical research examining the operationalization of the components of the model for use in engineering is just beginning [2, 4, 14, 19, 21], and current researchers are attempting to determine how these components be effectively taught and assessed. In this study we begin to answer these questions by focusing on teaching the Elements of Thought through two reflective writing assignments about problem-based learning projects and assessing student outcomes using two critical thinking rubrics.

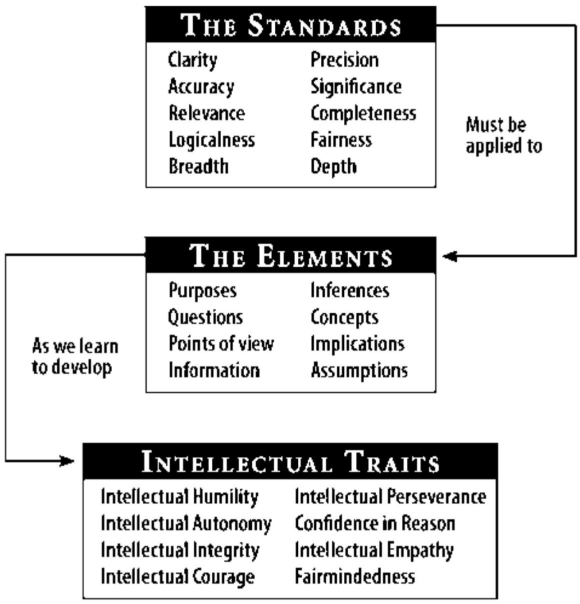

Fig. 1. Paul-Elder Framework for Critical Thinking, adapted from [17].

3. Current study

In an earlier effort to study the writing and critical thinking skills of first-year engineering students, the authors engaged in a research study that measured the effectiveness of an approach that encompasses the use of the Paul Model in developing writing assignments and by assessing writing and critical thinking skills and surveying engineering and writing attitudes utilizing grading rubrics developed at Oklahoma State University. Additionally, an affective measure (the Writing Attitudes Survey) was developed to assess students' attitudes and motivation towards engineering and writing [32, 33, 47]. While the results yielded positive improvements in student perceptions of themselves as writers, there were no significant differences shown in critical thinking from the beginning of the semester to the end as measured by grading rubrics. Few critical thinking interventions were implemented in this earlier study; this may have led to the lack of significant improvements in critical thinking skills measured by grading rubrics. In the current study, the integration of critical thinking interventions into the course from conception to evaluation was utilized to improve the opportunities for development of student critical thinking skills.

3.1 Purpose and research questions

The focus of this study was to determine whether or not critical thinking interventions administered throughout the semester would improve overall critical thinking scores over the course of the semester on two reports as measured by two assessment methods, both based on the Paul Foundation of Critical Thinking Model [17]. We also wanted to determine whether students would be more likely to incorporate the eight elements of thought into the correct subsection of the final report as a result of critical thinking interventions. Our research questions:

1. Will students' critical thinking skills be enhanced over the course of the semester as a result of instructor interventions as measured by differences in total scores on two rubrics, both based on the Paul Foundation of Critical Thinking Model?
2. Will students' critical thinking skills improve on final drafts of two reports as a result of feedback received from writing fellows on first drafts of the two reports as measured by differences in total scores and subscores of the same two rubrics?
3. Would students be more likely to place the eight elements of thought in the correct subsections of their second reports as a result of feedback received from writing fellows on their first reports, indicating that their critical thinking skills had improved?

3.2 Method

For this study, groups of FY students in Introduction to Engineering courses participated in two design activities and wrote two individual reports about these activities. Both reports required that students turn in a draft and final version. The reports were the focus of the study. The first project report was completed at the beginning of the semester prior to critical thinking and writing interventions and the second project report was completed at the end of the semester after interventions in order to compare differences in scores from Report 1 to Report 2. All reports were assessed using two rubrics, described below. The two reports and two methods of assessment were all based on the Paul Foundation of Critical Thinking Model, to examine whether using a single model to integrate the objectives and assessment of critical thinking skills within the context of writing in a semester-long course would lead to an increased level of critical thinking and writing skills for engineering students [17].

3.3 Participants

The FY students were distributed across four sections of Engineering, all one-credit Introduction to Engineering courses. Two sections focused on engineering math (ENGR 1113), 1 on chemical engineering (316) and 1 on entrepreneurship (307), with 74 students total enrolled in all 4 sections. Of the 74 students that remained enrolled in the sections at the end of the semester, 49 turned in a final version of both reports, actively attended class, were of age of consent, and agreed to participate in the research study. The 49 students had the following demographics at the time of the study:

- 7 were female (13%)
- 43 were freshman (88%), 4 were sophomores (8%) and 2 were juniors (4%)
- 27 of the students (55%) participated in a linked Composition 1 class that also had critical thinking interventions

3.4 First design project

All students completed Project 1 near the beginning of the semester prior to interventions. In this project, student teams designed Airplanes for the duration of one class period [32]. First, students formed teams. Teams were then given the following supplies: toothpicks, rubber bands, paperclips, Post–It Notes®, gum, Ziploc® sandwich bags, brown lunch bags, Tootsie Rolls®, and Life Savers®. Teams then had 5 minutes to determine how to manufacture their Airplanes and 10 minutes to build them. During this time, the instructor "interrupted" production with operational upsets (e.g. turn off lights for one minute to simulate a power outage). After completing the activity, individual students were required to write two drafts of reports based on the design activity, called the Airplane Design Report (Project 1).

The conceptual focus of the activity was for students to learn the difference between product and process design. The researchers designed the writing assignment based on the eight Elements of Thought from the Paul-Elder Critical Thinking Model [17]. The assignment required students to identify and explain each of the eight elements of thought as applied to the particular design activity. Fig. 2 contains the portions of the writing assignment that were written to specifically address the Paul-Elder eight elements of thought. Based on these instructions, it was expected that students would address each of the eight elements *and* that they would address the elements in specific subsections of their reports (See table 4 for the intended report subsection location of elements). Students were not explicitly told about this intended connection between subsections of the assignment and the Paul-elder critical thinking elements.

3.5 Second design project

For Project 2, the 3 groups of student teams participated in 3 different activities, all of which required writing two drafts of individual reports in the same style as Project 1:

1. The chemical engineers (ENGR 316) worked on a film canister rocket design activity. The focus of this activity was to consider the best propellant that would shoot the rocket the farthest. The activity was designed to highlight the similarities and differences between math and science.
2. The entrepreneurs (ENGR 307) worked on a business plan for either an existing patent, or an invention of their own.
3. The math group (ENGR 1113) participated in a variety of lab activities that demonstrated how engineers use math. This approach is part of the Wright State National Engineering Math consortium headed by Nathan Klingbeil [48].

After Project 2 activities were completed, students were required to write two drafts addressing the following student research and implication questions:

1. ENGR 316—Chemical Engineering
   a. Student Research Question—What is the

The purpose of this paper is for you to consider the differences between product and process design using information and evidence from your reading and from your Airplane Design Activity in order to understand the relationship of the two for engineering. (Your paper will consist of the following five sections.)

Introduction Your introduction should give background to the activity (including your definitions of product and process-from your sources) and your point of view about process and product design (the importance of process and product design in Engineering). Your research question is "What is the difference between product and process design?" and your thesis should answer this question.

Methods This part of your report should describe your team (team name and members). Describe the team prototype and why it was selected (the materials you used and the steps you went through to design your Airplane prototype). Then detail the manufacturing method of your final chosen prototype.

Results Describe the results of the product ranking and process evaluation (this should be presented in a graphic form -e.g. a table, graph, figure). (What ranking in the contest did your airplane receive?). How does this compare to other teams and why (what can you learn from looking at the other team prototypes and manufacturing processes)?

Conclusions This section should discuss the strengths and weaknesses of your product and process design tying that in with your team process. (Did team issues facilitate or hinder your product/process?). (You may compare your results with other teams using the data, pictures and video available.)

Implications The purpose of the Airplane Design Challenge experiment was to help you understand the difference between product and process design. Comment on your understanding of these two concepts. How do the results of your lab help you understand the importance of these concepts for Engineering? (How does product or process design affect the other and vice versa? Why is understanding these two concepts important for engineers?)

Fig. 2. Project One Report Assignment with Paul's Elements of Thought.

difference between science and engineering?
   b. Implication Question—How do the results of your lab help you to understand the importance of these concepts? (How does science or engineering affect the other and vice versa? Why is understanding these two concepts important?)
2. ENGR 307—Engineering Entrepreneurship
   a. Student Research Question—Why does an inventor need to understand business planning?
   b. Implications Questions—How do the results of your project help you understand the importance of business planning? Why is understanding this concept important?
3. ENGR 1113-Engineering Math
   a. Student Research Questions—How and why has your understanding of engineers' use of math changed this semester? (Addressing the following: What background in math did you personally have when you started OSU classes back in August? What were your beliefs and attitudes about math when you started OSU classes back in August?)
   b. Implications Questions—Of all of the math concepts you learned, which do you think you will use the most as an engineer? Of all the things you learned which do you think you are least likely to use as an engineer? How do you anticipate that the understanding of engineers' use of math you acquired this semester will help you in your classes and future experiences as a practicing engineer?

3.6 *Critical thinking instructor interventions*

Upon completion of the First Project Report, the course instructor assigned students in Chemical Engineering (ENGR 316) and Engineering Entrepreneurship (307) four critical thinking exercises from the book *Engineering Reasoning* by Paul et al. [17]. Students in Engineering Math (ENGR 1113) did not receive these interventions. First, students observed an object and answered questions based on the eight elements of critical thinking about its design. Second, they observed an 'invention', an ergonomic shopping cart, and did the same. Third, students analyzed information from a website focusing on topics and engineering (service learning, study abroad, social entrepreneurship, or ethics) for the eight elements. The fourth and final exercise was to examine a graphic from an article using the Intellectual Standards. These four exercises began in the third week of the semester and continued through thirteenth week of the semester. After completion of these four exercises, the students completed the Final Project Activity. Each student then wrote a first draft of the report to be submitted to a Writing Fellow for feedback, after which they wrote a Final Report, incorporating the Writing Fellow's feedback.

3.7 *Writing fellows*

Four undergraduate engineering students and one undergraduate English student were chosen as WFs (none were freshmen). The engineering students had taken the Introduction to Engineering course the year before and had been identified by the course instructor as excellent students and writers. The English student had been trained and worked as a writing fellow for the Oklahoma State University Writing Center. Writing fellows participated in a 20 hour training session prior to the start of the semester (see Damron & High [32] for additional information). Topics covered during training included writing as a process, grammar and mechanics, and conducting face-to-face tutorials [32].

All students in all course sections were required to turn in a draft, i.e. the Fellow Draft, of each Project Report prior to turning Final Reports in to instructors. Writing fellows read the reports, then filled out a checklist based on the requirements of the assignment and wrote a cover letter which addressed the strengths and weaknesses of each individual student's report based on the checklist. The checklist contained the same information as the Instructor Grading Rubric (see Appendix for Fig. 3). The writing fellow and each FY student then met for a 30 minute face-to-face fellow tutorial to discuss the fellow's comments on the report in a lab in the engineering building. The FY students then revised the reports and turned in the Final Drafts to the instructor, who then graded the reports.

3.8 *Evaluation instruments*

Two evaluation instruments were used to assess the student reports: the Instructor's Grading Rubric and the Surry Community College Critical Thinking Rubric (SCTR) [49]. The Instructor's Grading Rubric was based on the criteria of the assignment guidelines shown in Fig. 2, and did not include the Requirements section as shown in the Instructor's Grading Rubric (See Appendix, Fig. 3). The rubrics for the 3 different versions of the Project 2 Reports were very similar (totals for the reports were 50 points). The Project 1 and Project 2 reports were each worth 50 points (100 points total) and represented 16.7% of the total course points (600 points).

The 98 reports (2 each per 49 students) were also evaluated using the SCTR (See Appendix, Fig. 4).

This rubric was developed based on the Paul—Elder Elements of Thought. Two raters were trained and normed scores with one of the researchers and then evaluated final drafts of the student reports. In their comments, raters were required to use the SCTR to determine first whether or not the students included the required elements in their reports, and second, whether the elements were included in the intended subsection of each report based on the assignment. Raters were not aware that these elements were expected to be in specific subsections.

4. Results

The student reports on the design activities were assessed using two measures: the Instructor's Grading Rubric and the SCTR. Only students who completed both drafts of both projects were included in analyses. Prior to all analyses, we examined the strength of the relationship between the instructor's Grading Rubric total scores and the SCTR total scores for Report 1 and Report 2. For Report 1, the Instructor's Grading Rubric total score rating was highly positively related to the SCTR total score rating, $r = 0.71$, $p < 0.001$. For Report 2, the Instructor's Grading Rubric total score rating was highly positively related to the SCTR total score rating $r = 0.60$, $p < 0.001$.

4.1 Research question one: effect of instructor interventions on differences in overall rubric scores

Two-tailed t-tests showed that there were no significant differences in overall Instructor Grading Rubric or SCTR scores between students who received Instructor CT interventions (students in ENGR 316 and ENGR 307) and those who did not receive interventions (students in ENGR 1113) as a result of instructor interventions (all ts < 1.7; all ps > 0.05). Because there were no statistically significant differences in scores between groups as a result of instructor interventions, all groups were combined for all remaining analyses to gain power, except where noted.

4.2 Research question two: effect of writing fellow feedback on differences in overall rubric scores

Students who saw a writing fellow showed significantly more improvement in critical thinking skills as assessed by their Instructor Grading Rubric total scores and their SCTR total scores for both Project 1 and Project 2 than students who did not see a writing fellow (see Table 1 for rubric scores). There were a total of 50 points possible on the Instructor's Grading Rubric and 32 points possible on the SCTR. All t-tests were one-tailed; it was expected that students who saw a writing fellow would have higher total scores than students who did not, and the alpha level was set to 0.05.

Analyses showed that students who saw a writing fellow had higher overall scores on the Project 1 Final Report than students who did not see a writing fellow, as indicated by both Instructor Grading Rubric total scores, $t(47) = -4.22$, $p < 0.001$, 95% CI of the difference [= $-\infty$, –3.69], and SCTR total scores, $t(47) = -3.38$, $p < 0.001$, 95% CI of the difference [= $-\infty$, –1.65]. For the Project 2 Final Report (film canister rocket design for ENGR 316, business plan for ENGR 307, lab activities utilizing math for ENGR 1113) students who saw a writing fellow between draft one and the final draft had higher overall scores on the Project 2 Final Report than students who did not see a writing fellow, as indicated by Instructor Grading Rubric total scores, $t(47) = -1.90$, $p = 0.032$, 95% CIs of the difference [= $-\infty$, –0.54], and by SCTR total scores , $t(47) = -2.38$, $p = 0.01$, 95% CI of the difference [= $-\infty$, –1.26]. These results indicate that writing fellow feedback had a positive effect on overall Instructor Grading Rubric and SCTR scores.

4.3 Research question two: effect of writing fellow feedback on differences in instructor grading rubric subscores

To determine whether students' critical thinking skills improved as measured by Instructor's Grading Rubric Scores as a result of feedback received from writing fellows, Wilcoxon Signed-Rank tests for paired samples were conducted to test for differences in average subscores of critical thinking elements from Project 1 Report to Project 2 Report for students who turned in both drafts of Project 1 Report and Project 2 Report and who saw a writing fellow for both reports (See Table 2). The Introduction and Conclusions subsections were worth 5 points each; the remaining 4 subsections were

Table 1. Average Total Instructor and SCTR Rubric Scores for Project 1 and Project 2 by Writing Fellow Status

	Writing Fellow Visit	Project 1				Project 2			
Rubric		***N***	***M***	***SD***	***Md***	***N***	***M***	***SD***	***Md***
Instructor Grading	Yes	35	43.49	4.55	45.00	46	43.70	4.14	44.50
	No	14	37.36	4.68	37.50	3	39.00	4.58	40.00
SCTR	Yes	35	22.06	3.15	21.50	46	22.61	3.07	22.00
	No	14	18.79	2.80	19.25	3	18.33	1.26	18.50

worth 10 points each, for a total of 50 points possible. Results of one-tailed tests indicated statistically significant improvement in subscores for the Results, Conclusions, and Requirements subsections. The improvement from Project 1 Report to Project 2 Report approached significance for the Introduction subsection as well. Also see Table 2 for Cliff's delta (*d*) effect sizes for between groups and within groups for the difference between scores in Projects 1 and 2. Cliff's delta between indicates effect sizes for differences in groups subscores, while Cliff's delta within indicates effect sizes for individual differences in subscores. Cliff's delta conventions for small, medium, and large effect sizes are 0.147, 0.33 and 0.474, respectively. Effect sizes were in the "small" range for both between and within groups for the Introduction, Results, Conclusions, and Requirements subsections.

4.4 Research question two: effect of writing fellow feedback on differences in SCTR subscores

Wilcoxon Signed-Rank tests for paired samples were also conducted to test for differences in average subscores of critical thinking elements from Project 1 Final Report to Project 2 Final Report for students who had turned in both drafts of both reports and who saw a writing fellow for both reports (See Table 3) as measured by the SCTR. Each subsection was worth 4 points for a total possible 32 points. Results of one-tailed tests indicated a statistically significant improvement in subscores for the Information subsection.

4.5 Research question three: the effect of writing fellow feedback on location of elements by report subsection

The final research question was "Would students be more likely to place written content that contained the eight elements of thought in the correct subsections of their second reports as a result of feedback received from writing fellows on their first reports, indicating that their critical thinking skills had improved?". The eight elements of the Paul-Elder model were intended to be included in the five subsections of both reports listed below in Table 4, which includes data for the 33 students who completed both drafts of both reports and who saw a writing fellow for each report. Shaded boxes indicate the correct, or intended, location of elements for each subsection (note that there are two intended locations for the point of view element: introduction and methods). Table 4 shows the percentage of elements included in each subsection for the Project 1 and Project 2 Final Reports. The bolded numbers indicate that greater than 50% of students included elements in that particular subsection for both papers, regardless of "correct" location. Two asterisks (**) indicate differences of at least ten percent in subsection element location from Project 1 to Project 2 Report.

Table 2. Instructor Grading Rubric Average Report Subscores, Differences, and Effect Sizes for Project 1and Project 2 (N = 34).

Report Subsection	Project 1			Project 2			Difference from Project 1 to Project 2			
	M	*SD*	*Md*	*M*	*SD*	*Md*	*V*	*p*	d_b	d_w
Introduction	3.67	1.01	4	4.08	0.89	4	138	0.013*	0.224	0.224
Methods	8.82	0.97	9	8.45	1.89	9	320	0.86	0.005	0
Results	8.27	1.77	9	9.08	1.66	10	180	0.0001**	0.312	0.323
Conclusions	4.10	0.98	4	4.41	1.02	5	135	0.057	0.213	0.204
Implications	8.00	2.41	9	8.14	1.98	8	371.5	0.41	0.013	0.020
Requirements	8.88	1.17	9	9.24	0.99	10	156	0.018*	0.189	0.204
TOTAL	41.73	5.33	43	43.41	4.27	43				

Note: *$p < 0.05$.

Table 3. Surry Community College Critical Thinking Rubric Average Report Subscores, Differences, and Effect Sizes for Project 1and Project 2 (N = 34)

Critical Thinking Element	Project 1			Project 2			Difference from Project 1 to Project 2			
	M	*SD*	*Md*	*M*	*SD*	*Md*	*V*	*p*	d_b	d_w
Purpose	3.12	0.51	3	3.22	0.33	3	54.00	0.15	0.142	0.184
Key Question, Problem, Issue	2.76	0.55	2.5	2.91	0.49	3	100.50	0.15		
Point of View	2.64	0.42	2.5	2.73	0.59	2.5	140.00	0.54	0.184	0.204
Information	2.60	0.49	2.5	2.80	0.47	3	63.00	0.03*	0.295	0.306
Concepts	2.76	0.55	2.5	2.80	0.47	3	147.00	0.45	0.145	0.184
Assumptions	2.76	0.45	2.5	2.77	0.47	3	98.50	0.81	0.06	0.184
Interpretations, Inferences	2.62	0.63	2.5	2.86	0.63	3	124.50	0.12	0.246	0.310
Implications, Consequences	2.71	0.50	2.5	2.86	0.52	3	109.00	0.23	0.130	0.224
OVERALL	21.94	3.17	21.5	22.97	3.12	22				

Table 4. Location of Elements of Thought in Each Report Subsection for Final Drafts of Project 1 and Project 2 (*N* = 34)

Critical Thinking Element	**Introduction**		**Methods**		**Results**		**Conclusions**		**Implications**	
	P1	**P2**	**P1**	**P2**	**P1**	**P2**	**P1**	**P2**	**P1**	**P2**
Purpose	**100**	**100**	0	0	0.03	0	0.03	0.03	**100**	**100**
Key Question, Problem, Issue	**100**	**100**	0	0	0.06	0	24.2	15.2**	**100**	**100**
Point of View	**100**	**100**	42.4	**57.6****	**75.8**	**97.0****	**57.6**	**51.5**	**75.8**	**72.72**
Information	0	0	**97.0**	**100**	**100**	**100**	**81.8**	**93.9****	0	0
Concepts	**66.7**	**54.5****	**75.8**	**84.8****	**90.9**	**93.9**	**57.6**	**70.0****	**93.9**	**87.9**
Assumptions	0.03	0.06	24.2	21.2	**78.8**	**57.6****	**100**	**100**	**57.6**	**93.9****
Interpretations, Inferences	0.03	0	0.06	0.06	48.5	33.3**	**100**	**100**	**78.8**	**93.9****
Implications, Consequences	30.3	24.2	0	0	0	0	57.6	33.3**	**100**	**100**

All students correctly included information about the elements Purpose, Key Problem, Question, or Issue, and Points of View in the intended subsection location Introduction for both reports, and over 50% of students also included Points of View correctly in the second intended subsection, Methods. However, all students also incorrectly incorporated information regarding the elements Purpose and Key Question, Problem or Issue into the Implications subsections of both reports. Furthermore, over half of the students (and in some cases nearly all students), incorrectly included information about the element Points of View incorrectly into the Results, Conclusions, and Implications subsections. All students also incorporated content regarding the element Information in the correct subsection (Results) for both papers; however, all students also incorporated content regarding Information incorrectly into the Methods subsection of the Project 2 Report, and over 90% included Information incorrectly in the Conclusions subsection of the final report. Over 80% of students included Concepts correctly in the Conclusions subsection of Project 2 Report; however, over 50% (and sometimes well over 50%) of students also included Concepts in every other subsection of Project 2 Report. Information regarding the element Assumptions was intended to be discussed in the Methods subsection, but fewer than 25% of students correctly included information about Assumptions in this subsection for Project 2 Report, and instead included this information in the Results, Conclusions, and/or Implications subsections. Information about the element Interpretations and Inferences was intended to be discussed in the Conclusions subsection, and 100% of students correctly did so; however, over 90% of students also discussed this element in the Conclusions subsection of the Project 2 Report; this percentage was actually *higher* than for Project 1 Report. Information about the element Implications and Consequences was to be discussed in the Implications subsection and 100% of students did so for both reports. Finally, over 30% of students also incorporated information about this element incorrectly into the Introduction and Conclusions subsections for Project 2 Report, although this was actually an improvement as 57% had done so in Project 1 Report.

5. Discussion

5.1 Research question one: effect of instructor interventions on differences in overall rubric scores

We found that instructor interventions in this study were not effective in improving critical thinking skills. Students enrolled in ENGR 316 and ENGR 307 received four critical thinking exercises from the book *Engineering Reasoning* by Paul et al. and students enrolled in ENGR 1113 did not. There were no differences in any rubric scores as a result of these interventions [17]. The most likely explanation for these results was the lack of explicit instructions from faculty. It was assumed that students who received critical thinking interventions would extrapolate knowledge gained from these exercises to all assignments in the course and particularly to those that specifically addressed critical thinking. However, this was not the case. Lewis et al. found that similar instructor interventions were not effective in improving critical thinking skills, and they are also revising their methodology to include specific instructions to students about the Paul-Elder model as it applies to assignments [14, 17]. There were two important difference between the two studies: students received points that ultimately affected their final grades in our study, while students in Lewis et al. did not, and in our study, we used two critical thinking rubrics, both of which provided us with detailed subscores and overall scores, while Lewis et al. used a holistic rubric that provided only a general score [14]. Furthermore, recent research shows that students often do not apply critical thinking concepts learned in one context to others unless specifically told to do so [4, 14, 16, 22]. Students typically apply cognitive strategies only to the currently assigned project and do not extrapolate strategies learned in one context to another unless they are told to do so [50]. In a

2008 meta-analysis examining effective methods for teaching critical thinking skills, implicit instruction was found to be less effective than explicit instruction [22]. Based on their results, Lewis et al. recommend that faculty adopt the language of the Paul-Elder model for use when giving assignments and describing activities to help students understand that critical thinking is not discipline specific [14]. Based on our results, we will continue to use and revise our rubrics, and are considering the possibility that providing writing fellows and even students with some version of the rubrics may be beneficial in improving critical thinking scores. We add that students should be told specifically to apply the Paul Elder model to written assignments in all of their courses.

5.2 Research question two: effect of writing fellow feedback on differences in overall rubric scores

Students who saw a writing fellow showed significantly more improvement in critical thinking skills as assessed by their Instructor Grading Rubric total scores and their SCTR total scores for both Project 1 and Project 2 than students who did not see a writing fellow (see Table 1 for rubric scores). Average overall scores for both projects and both rubrics were about 20 points higher for both projects for students who saw a writing fellow. Similar results were found in a study examining effects of writing tutoring in a junior-level construction management course, although students had also received a 50 minute writing tutorial at the beginning of the course, which also may have contributed to improvements [44]. The authors reported improvements of 10 points from report 1 to report 2. Working with writing fellows also improved scores significantly for students in a literary interpretation course requiring intensive analytic writing and original research for a series of three reports [43], and in a freshman composition course [45]. It is important to mention that the goal in the studies discussed here was to improve written communication, not critical thinking skills. Clearly, working with writing fellows helps students improve writing skills, and in the current study, interventions were effective in raising overall measures of critical thinking, which many link to writing skills [15, 16, 27–29, 30]. That being said, effects on more specific measures of critical thinking were small, and instructor interventions were not effective in improving first year students' critical thinking skills as measured by subscores of the two critical thinking rubrics.

The effects of writing fellow feedback are likely not the only cause of differences in scores between the two groups of students. The benefits of writing and problem-based learning to critical thinking tend to be cumulative; that is, the more frequently a student practices these two types of assignments in conjunction with explicit critical thinking interventions from faculty, the better their critical thinking practices become, as shown in recent research [2, 21]. One would expect that on average, students who did not see a writing fellow would tend to have lower grades in general than students who did, and in most courses, there are a few students whose scores are well above average regardless of interventions. Furthermore, writing skills should improve at least slightly over the course of the semester, at least for students that turned in both writing assignments. The goal in the current study was to examine effective methods for improving critical thinking skills for the average student; as such, we cannot draw conclusions about students that did not fully participate. Finally, although there were significant improvements in overall scores for both rubrics, improvements were seen for some, but not all, subscores for each rubric. Possible reasons for this will be discussed in the next section.

5.3 Research question two: effect of writing fellow feedback on differences in instructor grading rubric subscores

There were statistically significant improvements in average subscores for the Results, Conclusions, and Requirements subsections of the Instructor Grading rubric, and improvement in the Introduction subsection approached significance as well. The largest positive changes were found in the Results subsection of Report 2, which contains the element Information. The requirements of this subsection included describing and presenting data, discussing ratings of product and process design and the reasoning for such rankings, and comparing the student's team to other teams, all of which required critical thinking. Improvements in the Conclusions subsection, which contains the element Interpretations and Inferences, is also of interest, because it required that students analyze and synthesize information and present their results in terms of possible outcomes. Structured feedback from writing fellows, as well as experience from Project 1 Report, was particularly beneficial for students when writing these subsections for Project 2 Report. The Requirements subsection related to the technical and mechanical aspects of the report, and one would expect that there would be improvements in these subscores from Project 1 Report to Project 2 Report, as result of feedback received from writing fellows and instructors, and from experience students gained in Project 1.

Instructor Grading Rubric subscores for the Methods and Implications subsections dropped slightly (although not statistically significantly) from Project 1 Report to Project 2 Report. This may have occurred because Project 2 was more complicated than Project 1. Also, students were supposed to include information about the element Point of View as it pertained to how student teams had chosen a particular design in the Methods subsection, but many failed to do so adequately, or addressed this requirement in other subsections. Information about the elements Concepts and Implications and Consequences was supposed to be addressed in the Implications subsection, which required students to incorporate these concepts with what they discovered in their activities. Students struggled with this subsection in this study.

5.4 Research question two: effect of writing fellow feedback on differences in SCTR subscores

For the SCTR, only the subscores for the Information subsection showed statistically significant improvements; improvements in the remaining subscores were not statistically significant. How can it be possible that there were significant improvements in overall scores for both rubrics, but only for a few of the subscores of the Instructor Grading Rubric and only one subscore of the SCTR? It is likely that this occurred because holistic (overall) scores can provide only a rough ranking of student abilities; whereas subscores provide detailed information about the changes in abilities for each dimension of interest [16]. Overall scores for both rubrics were obtained by totaling all subscores; thus, even small improvements in one or more subscores would result in higher overall scores. Because of this, changes in subscores provide more information about improvements, or the lack thereof, in critical thinking abilities. It is also possible that the subscores of one of the rubrics provide more accurate information about the Paul-Elder model of critical thinking elements than the other. One could argue that the Instructor Grading Rubric subscores provided more accurate information about the eight elements of thought than did the SCTR; however, it is also possible that instructors and SCTR raters differed in their ratings of each critical thinking element. Finally, writing fellows provided feedback based on the Instructor Grading Rubric rather than the SCTR. If writing fellows had been aware that the eight elements of thoughts were to be addressed by students, they could have provided the appropriate feedback.

Writing fellows are clearly beneficial in improving students' overall scores of critical thinking; these benefits are not as clearly present at the subsection level of reports. It is important to mention that we did not have enough non-native English speaking students in our sample to determine whether writing fellow interventions were equally effective for those whose first language is not English; we plan to address this in future research through the use of a longitudinal study. We would also like to point out that structured feedback provided by writing fellows does not increase instructor workload, and in fact, cuts down on instructor grading time of final drafts [36]. Training can and should be provided for writing fellows or teaching assistants, see Damron and High [32] and McGrann et al. [36] for additional information.

5.5 Research question three: effects of writing fellow feedback on location of elements by report subsection

The final research question asked whether writing fellow feedback students received on Report 1 would result in more students including the eight elements of thought in the intended subsections of Report 2. See Table 5 for the intended location of each element of thought by subsection in each report (notice that the element Point of View was intended to be incorporated into 2 subsections):

Improvement in location of elements from Report 1 to Report 2 were seen in the Methods subsection, with significantly more students including information about Point of View correctly in this subsection. Other improvements from Report 1 to Report 2 involved significantly *fewer* students including information in incorrect subsections for the elements Key Problem, Question, Issue, Concepts, Assumptions, Interpretations and Inferences, and Implications and Inferences. However, significantly *more* students incorrectly incorporated information about the elements Point of View, Information, Concepts, Assumptions, and Interpretations and Inferences in various subsection of Report 2 than Report 1. Overall, students were best at incorporating the element Implications and Consequences correctly into the subsection Conclusions. For all other elements, even when they correctly included information about the appropriate element into the correct subsection, they also included information about those elements incorrectly into other subsections. For example, all

Table 5. Intended Location of the Eight Elements of Thought in Each Report Subsection

Subsection	Element of Thought
Introduction	1. Purpose 2. Key question, problem, or issue 3. Point of view
Methods	3. Point of view 6. Assumptions
Results	4. Information
Conclusions	7. Interpretations and inferences
Implications	5. Concepts 8. Implications and consequences

students correctly included information about the elements Purpose, Key Question, Problem, Issue, and Point of View in the Introduction subsection of both reports; however, information about these elements was also incorporated into the incorrect subsections for both reports as well. The same pattern held for the elements Information, Concepts, Interpretations and Inferences, and Implications and Consequences: Students typically incorporated information about these elements in the correct location for both reports, but they also incorporated it into incorrect locations. Students struggled most with the element Assumptions, with fewer than 25% incorporating information about this element into the intended subsection location Methods for both reports. Instead, this information was incorporated incorrectly into nearly all the subsections.

These results indicate that students have begun to grasp some, but not all, aspects of these elements of critical thinking as described by the Paul-Elder model, and are similar to results found in a recent study in which assignments specifically addressed the Paul-Elder model elements of thought [4]. The majority of students in Thompson et al.'s study were best at identifying Purpose, Concepts, and Key Question, Problem, Issue, although they also had some difficulty identifying these concepts. In their study, as in ours, students consistently struggled with Assumptions, and had difficulty with Point of View as well. Thompson et al. believe that this may have occurred in their study in part because faculty did not adequately convey the meaning of these elements to students [4]. For example, some faculty in their study had referred to Assumptions as meaning assumptions *about* engineers as opposed to assumptions *made* by engineers. They also pointed out that some faculty had trouble answering student's questions about Point of View. This is certainly an important possibility to consider. In addition, students in our study were not given specific instructions relating the elements to the assignment, but they struggled with the same elements. This suggests that students actually do have a more difficult time grasping concepts related to Assumptions and Point of View. It is possible that this occurred in part simply because students are just beginning to think about these two concepts, whereas they have had more practice in dealing with the somewhat more concrete concepts underlying Purpose, Key Question, Problem, Issue, Interpretations and Inferences, and Implications and Consequences.

Data from this and other studies show that students grasp some concepts related to the elements Purpose, Key Question, Problem, Issue, Interpretations and Inferences, and Implications and Consequences fairly well, and have considerably more difficulty with Assumptions and Point of View [4]. Understanding that both faculty and students need clarification about Assumptions and Point of View, we can address this in future research by providing faculty, writing fellows, and students with better explanations of these elements. Structured feedback from writing fellows has proved beneficial in helping students improve overall critical thinking scores over the course of one semester, and to a significantly lesser extent, improving subscores based on the Paul-Elder model's eight elements of thought in this study.

6. Conclusions

In the current study we have extended the engineering research to include the use of structured feedback provided by writing fellows. We found that using the Paul-Elder model's eight elements of thought to operationalize critical thinking concepts in conjunction with problem-based learning, writing for reflection, and structured feedback from writing fellows was productive in improving the overall critical thinking scores based on two rubrics of students within the context of lower-level engineering courses. However, we found that student critical thinking subscores improved on only one of the subscores for one rubric and three on the second, suggesting that students would benefit from explicit instructions regarding assignment subsections. To address this in the future, we will provide writing fellows with explicit instructions regarding the elements of thought and instruct them to provide students with feedback accordingly when returning their report drafts. We found that instructor critical thinking interventions were not effective in this study and they will be revised to include explicit instructions to students regarding the use of critical thinking in written assignments in our future research. Based on our results, we suggest that the integration of written assignments based on the Paul-Elder model along with structured feedback from writing fellows can be combined with problem-based learning into the engineering curriculum can be beneficial in teaching critical thinking skills. These methods could be incorporated into course objectives and be explicitly addressed in multiple ways.

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Appendix

Introduction	______**/5**
Background to activity	1
Clear and specific definition of product/process design	1
Point of view of the importance of product and process design in engineering	1
Thesis statement that answers "What is the difference between product and process design?"	1
Correct use of sources	1
Methods	______**/10**
Describe team	2
Clear description of team's decision making process – selection of airplane	2
Description of team prototype	2
Materials used	2
Manufacturing method	2
Results	______**/10**
Discussion of ranking in both product and process design	2
Clear presentation of team data (in graphic form)	2
Reasons for your teams rankings	3
Comparison to other teams	3
Conclusions	______**/5**
Strengths/weaknesses of individual product	1
Strengths/weaknesses of team product and process	2
Description of team dynamics and the effect on process/product design	2
Implications	______**/10**
Comments on your understanding of the two concepts of product and process design (differences in and importance of)	4
Comments on how product and process design affect each other	3
Comments on why understanding these concepts is important to engineers	3
Requirements	______**/10**
Submit to D2L dropbox/Microsoft word	1
3-5 pages/double spaced	1
1" margins/12 point font	1
Section headings/number pages	1
Bibliography (on separate page) MLA/APA	2
Grammar and spelling	2
Clarity in writing	2

Fig. 3. Project 1 Instructor Grading Rubric.

1. Purpose: ______/4
Does the student demonstrate a clear understanding of the assignment purpose?
2. Key Question, Problem or Issue: ______/4
Does the student clearly define the issue or problem, accurately identify the core issues, and appreciate their depth and breadth?
3. Point of View: ______/4
Does the student identify and evaluate relevant significant points of view? Does the student demonstrate fair-mindedness toward the problem? Does the student distinguish between his/her point of view and the source's point of view?
4. Information: ______/4
Does the student gather sufficient, credible, relevant information (statements, logic, data, facts, questions, graphs, assertions, observations, etc?) Does the student include information that opposed as well as supports the argued position? Does the student distinguish between information and inferences drawn from that information?
5. Concepts: ______/4
Does the student identify and accurately explain/use the relevant key concepts?
6. Assumptions: ______/4
Does the student accurately indentify assumptions (things taken for granted)? Does the student make assumptions that are consistent, reasonable, and valid?
7. Interpretations, Inferences: ______/4
Does the student follow where evidence and reason lead in order to obtain defensible, thoughtful, logical conclusions or solutions? Does the student make deep (rather than superficial) inferences? Are the inferences consistent?
8. Implications, Consequences: ______/4
Does the student identify the most significant implications and consequences? Does the student distinguish probably from improbable implications?

4 = Thinking is exemplary, skilled, marked by excellence in clarity, accuracy, precision, relevance, depth, breadth, logicality, and fairness
3 = Thinking is competent, effective, accurate and clear, but lacks the exemplary depth, breadth, and insight of a 4
2 = Thinking is inconsistent, ineffective; shows a lack of consistent competence: is often unclear, imprecise, inaccurate, and superficial
1 = Thinking is unskilled and insufficient, marked by imprecision, lack of clarity, superficiality, illogicality, and inaccuracy, unfairness.

Fig. 4. Surry Community College Critical Thinking Rubric.

Lynnette Michaluk is a Research Assistant Professor in the Center for Excellence in STEM Education at West Virginia University. She most recently worked as a Visiting Assistant Professor of Psychology at Oklahoma State University, where she taught undergraduate quantitative methods and social psychology. She also worked as a research associate for the Chemical Engineering Department at Oklahoma State University on projects examining the effects of critical thinking and writing interventions on critical thinking skills of undergraduates in engineering. She received her doctorate in Psychology at Oklahoma State University in 2009. Her current research interests include increasing the number of students who pursue STEM degrees, improving the retention rate of undergraduate students in STEM education, and critical thinking and writing in STEM.

Jon Martens is a doctoral candidate in the Occupational Education Studies program at Oklahoma State University. He was previously an Instructor in the College of Business and Technology at Rogers State University, where he taught courses in management information systems, computer literacy, and computer programming. Prior to joining Rogers State University, he was an information technology and senior instructional designer at IBM. His research interests focus on the application of virtual reality technologies and self-regulated learning strategies to workforce education.

Rebecca Damron is an Associate Professor of English, Director of the Writing Center, and Director of the OSU Writing Project at Oklahoma State University. Her writing center and writing project work feed her passion for community engagement. She received her Ph.D. in Applied Linguistics in 1997. Her research interests include interdisciplinary writing, and writing center discourse.

Karen High is the Associate Dean for Undergraduate Studies in the College of Engineering and Science at Clemson University. She came to Clemson in May 2015 after 24 years at Oklahoma State University, where she most recently served as Professor of Chemical Engineering and as Director of Student Services. Dr. High completed her doctorate in Chemical Engineering at Pennsylvania State University in 1991. Her research interests include Creativity, Critical Thinking, Writing, Mathematics, and Entrepreneurship in Engineering Education; Engineering for K-12 Teachers and Students; and Women in Engineering. High has generated over $4.5M of research funding, and she has mentored more than two dozen graduate students.