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# Work-in-Progress: Hands-on Critical Thinking Unit Integrated into in Freshman and Senior Chemical Engineering Courses

**Dr. Matthew Lucian Alexander P.E., Texas A&M University - Kingsville**

Dr. Alexander graduated with a BS in Engineering Science from Trinity University, a MS in Chemical Engineering from Georgia Tech, and a PhD in Chemical Engineering from Purdue University. He worked for 25 years in environmental engineering consulting before joining the faculty at Texas A&M University-Kingsville

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## Introduction

This work-in-progress paper presents the addition of a critical thinking course module into two chemical engineering (ChE) courses at Texas A&M University-Kingsville (TAMUK). Numerous articles have been published on critical thinking, however the literature is limited on the practical aspects of incorporating critical thinking skills into engineering education. This may be related to instructors finding it challenging to explain what constitutes critical thinking as related to engineering, and to the challenge in actually teaching and assessing critical thinking in engineering courses [1,2,4]. However, critical thinking skills have benefited this instructor in the analysis of problems and development of solutions over a 25-year career in the engineering consulting industry. Thus, critical thinking is a very important, though infrequently taught, aspect of engineering problem solving [1], and is important to the success of student's future engineering careers [2,3,4]. This paper describes the incorporation of a critical thinking module into a freshman introductory course and a senior design capstone course at TAMUK. The research question that was addressed in this effort was "Can integration of critical thinking in a freshman or senior engineering class improve student's readiness and confidence in addressing complex engineering problems they will face with future industry employers?" A purpose in presenting this paper as a work-in-progress is to solicit feedback from other faculty who may have engaged in similar instruction on critical thinking in engineering courses.

There are different definitions in the literature for critical thinking. One definition that is relevant to engineering work is "the ability to think clearly and rationally, understanding the logical connection between ideas, and the connection between the abstract and the physical world". This definition is appropriate to engineering analysis and design because it lays out a connection between the abstract (ideas or theories) and real-world applications (physical world which engineers design). A more extensive definition that this instructor used when introducing the students to this unit was "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 making decisions" [modified from 1,4]. This particular definition utilizes higher-order thinking skills (conceptualizing, applying, analyzing, synthesizing, and/or evaluating), which are synonymous with the higher-order thinking skills of Bloom's taxonomy (analyze, evaluate, create). These higher-order thinking skills are integral parts of the engineering design process, namely the steps "generate alternative solutions", "evaluate alternatives", and "evaluate prototype testing" [1,4].

## Development and Implementation

The module on critical thinking was developed and implemented in two Fall 2024 courses simultaneously, a freshman introduction to engineering course (GEEN 1201 Engineering as a Career) and the first semester course (CHEN 4316 Chemical Process Design I) of a two-semester senior design capstone sequence. The latter course serves to bring together the technical content of previous ChE courses into a culminating capstone design experience. The course introduces students to process simulators, and includes group project assignments which challenge the students in understanding and applying sophomore and junior level course content. The critical thinking module was presented alongside the senior level course content, with an emphasis on the importance of critical thinking to the students' upcoming engineering careers. The enrollment in CHEN 4316 for Fall 2024 was 17 students. The introduction to engineering course GEEN 1201 Engineering as a Career is the course that introduces freshmen to the chemical and natural gas engineering majors. This course introduces freshmen to the engineering design process, and allows them to experience design through a team-based project prescribed by the instructor. The intent in this course was to introduce the concept of critical thinking, as it relates to engineering problem solving, to freshman students who are embarking on their engineering academic career. The enrollment in GEEN 1201 for Fall 2024 was 31 students, and one of these students did not participate in the course after the second week of the semester. Thus, the effective course enrollment was 30 students. For both courses, the learning objective for this unit was to understand critical thinking concepts and utilize critical thinking in analysis, evaluation, or synthesis portions of an engineering design project.

The critical thinking module included in both of these courses was developed in part based upon techniques employed by other faculty in engineering [2,3]. The course module developed here consisted of three elements, which were (1) a lecture to introduce critical thinking and why it is important to advanced problem solving and career success for engineers; (2) an in-class hands-on critical thinking activity or visual exercise; and (3) a group engineering project in which the use of critical thinking skills was encouraged. The critical thinking lecture was presented to the students in single class period towards the beginning of the semester. This timing was selected so that the students could use what they learned from the critical thinking module in their subsequent group project during the semester. The in-class activity was conducted on the same day as the critical thinking lecture.

The critical thinking in-class group activity involved assigning to student groups one of the five following hands-on or visual exercises (a) calculating the speed of the tip of a wind turbine blade; (b) analyzing a rain gauge which measures cumulative precipitation with inch markings that are spaced greater than one inch apart; (c) identifying the source of condensation on a glass of ice water; (d) estimating the difference in gas versus liquid mass densities as evident from a gas-evolving reaction; and (e) estimating the amount of pore volume present in a jar of sand or rocks. The intent of each activity was for students to make visual observations, then recall and utilize technical concepts or simple formulas from foundational STEM classes (math, physics, or chemistry), and to put together the two pieces of information to solve the problem posed. This generally follows the first definition of critical thinking given above (think clearly, understanding connections between ideas, and connections between the abstract and the physical world). However, the in-class assignment questions (see Results below) were not necessarily constructed to rigorously assess the student's critical thinking per each of these elements. These in-class exercises are described in greater detail below:

a. Students were provided with a video of a rotating wind turbine, and were asked to calculate the speed of the tip of the blade in feet per second or miles per hour. This required students to measure the time for one rotation of the blades, estimate the length of one wind turbine blade from visual clues in the picture/video (or from personal experience), and use the formula for circumference of a circle and the formula for velocity as distance divided by time to calculate the blade tip speed.

b. Students were provided a plastic rain gauge that included a clear plastic sight tube with one-inch precipitation markings and a funnel for precipitation collection situated at the top of the plastic sight tube. The students were asked to explain the basis for the inch markings on the sight tube being greater than one inch apart. They were expected to identify the ratio of areas of the top and bottom openings of the funnel as the basis for the sight tube inch markings.
c. Students were provided with two glasses, each containing ice water, one of which was an insulated glass and the other being a non-insulated glass. The students were asked to explain why there was condensation on the outside of the non-insulated glass and not so much on the insulated glass, as well as the source of the moisture present predominantly on the outside of the non-insulated glass.
d. The course peer mentor conducted a demonstration of the evolution of oxygen gas from the decomposition of 3% hydrogen peroxide in an aqueous solution, catalyzed by baker's yeast. Students were asked to estimate the difference in densities for hydrogen peroxide in water and the oxygen gas evolved from this decomposition, as observed in a foam phase, based on their observations and the initial hydrogen peroxide concentration information. They were expected to recognize that the original density of oxygen in the aqueous solution would be close to that of water, and then they were expected to estimate the gas density based on mass of the oxygen evolved as gas and the volume it occupied, as indicated by the foam generated.
e. Students were provided with a jar of sand or gravel and water in a container that included volume markings, and then tasked with determining the volume of the pore space that exists between the sand or gravel particles, without dumping the material out of the jar. They were expected to measure carefully the incremental volumes of water added to fill the pore space present in the jar, prior to water appearing as a free liquid surface above the sand or gravel particles.

## Results

The assessment of the overall effectiveness of this critical thinking module incorporated into the two ChE courses is based on class scores on the critical thinking in-class group exercise, on the critical thinking final exam question (a bonus question), and finally on the short survey administered to the students both prior to the critical thinking module presentation and again at completion of the course. In particular, certain survey questions are related to the readiness and confidence aspects of the research question (see below). The survey administered to the students was reviewed and approved by the TAMUK Institutional Review Board (IRB-FY2024-59). In the in-class exercise, each group of 3-4 students was asked to answer the following set of questions related to their assigned critical thinking challenge. The students submitted responses on the same day.

The in-class assignment questions were:
1. What is your group's answer to the question posed about this particular scenario? Your answer should be as quantitative as possible.
2. What technical info (equations, formulas) or scientific principles did you use from your STEM background or previous courses?
3. Was there any information you used that was based on common sense, or past experience?

4. Are there any conclusions or generalizations that you can draw from the analysis performed?

The class average score on this in-class group assignment for the capstone design class was 94.6 (standard deviation of 3.7), with scores ranging from 89 to 100. The scores on this in-class group assignment for the freshman class were similar, with a class average of 92.7 (standard deviation of 3.3), with scores ranging from 90 to 100. Generally, a score of 90 or above was assigned if the student group provided a reasonable answer to at least two of the four questions. In future assessment of this in-class assignment, aspects of critical thinking can be related to the above questions as follows: (a) thinking clearly and rationally, which relates to question 2; (b) logical connections between ideas, which relates to questions 2 and 3; and (c) connection between the abstract and the physical world, which relates to questions 1, 3, and 4.

In the final exam for each course, a 5-point bonus question was posed asking the students to relate how they may have used critical thinking in their group projects or senior design project during the course. A bonus problem was utilized in this case due to the limited importance of this unit compared to other units and learning objectives in each of the two courses. For this question, a score of 3 or higher out of 5 was assigned if the student's answer related directly to their project, and exhibited some recognition of critical thinking, while lower scores of 1 or 2 were assigned when the student answer was only about the course in general, or was very vague in reference to their project. The class average score result for the senior capstone class on this question was 3.2/5.0 (standard deviation of 1.68), with individual scores ranging from 0 to 5, and 94% of students providing some response. The class average score results for the freshman class on this question was 2.7/5.0 (standard deviation of 1.7), again with individual score results ranging from 0 to 5 and 87% of students providing some response. The grading of these bonus questions did not include separate assessment of the clear and logical thinking, connection between ideas, or connection between abstract to physical world aspects of critical thinking. These results indicate a higher result for the senior students as compared to the freshman for this particular exercise. This difference between the academic levels is an area that future research may explore for better understanding.

Some specific statements from the final exam question for the senior capstone course that indicate application of critical thinking by several students are given below.

- *Critical thinking assisted me in the creation of a PFD (process flow diagram) for our group project 1A, when given only general process description information from several sources.*
- *Critical thinking helped me to understand the development and representation of heat flows in the cascade diagram portion of the heat integration problem of group project 3, as well as in recognizing errors and correcting them in calculating intermediate temperatures in the final heat exchanger network of this same group project.*
- *Critical thinking helped me to come up with the correct values for the operating specification of reflux ratio on one of the homework problems on distillation while using the RadFrac column in an Aspen simulation.*

Some specific statements from the final exam question for the freshman course that indicate application of critical thinking by several students are given below.

- *Realizing that the difference in oil and water densities is key to mixing and separating of phases in the liquid-liquid extraction project.*

- *Calculating between sizes used in the prototype and the sizes needed in the full-scale application of the design of a solar-powered pump system.*
- *Calculating scale up of a water treatment canister used to remove an organic contaminant to make water suitable for drinking.*

These specific statements from both courses suggest the students are gaining in their readiness to recognize and utilize critical thinking in the engineering problems posed to them.

Finally, the survey prepared for this effort posed to the students five statements regarding critical thinking, and requested their response on a 5-point Likert scale, using 1 = strongly disagree to 5 = strongly agree. The statements included in this survey are listed below, and the average Likert-scale responses are given in Table 1 for both senior and freshman courses. The survey responses indicate an increase ranging from 0.13 to 0.31 points between the pre- and post-surveys for the senior class, and an increase ranging from 0.36 to 0.58 points between the pre- and post-surveys for the freshman class. This demonstrates that a positive impact occurred due to the exposure of the students to the critical thinking module. For both classes, the standard deviations for each question were higher in the pre-survey as compared to the post-survey. This suggests that the students came to realize critical thinking is important in the application of engineering concepts and principles to real-world problems after exposure to the module..

The student survey statements are:

1. Critical thinking is an important skill for engineering students and working engineers to apply as part of the engineering design process.
2. Critical thinking is important in the application of engineering concepts and principles to the real-world during engineering analysis activities.
3. Critical thinking plays an important role in the engineering design process, specifically in the development of innovative design solutions.
4. Critical thinking is a skill which will be important for me to apply in my future engineering work as a chemical process or design engineer.
5. Critical thinking is an important skill which I wish to further develop in order to be a successful engineer in my future career.

Questions 1, 2, and 3 are intended as those which relate to the “student readiness” aspect of this project. Questions 4 and 5 incorporate self-references of the student (“me” or “I”), and are thus those which relate more to the “student confidence” aspect of this project. In reflection on the survey statements and the results obtained to date from implementation of the module in two courses in one semester, the instructor intends to revise statements towards statements that are more self-directed, namely using “I believe”, “I can”, or “I understand” type of statements, and that more clearly relate to student’s interest in and recognition of critical thinking in their engineering analysis and design academic work.

Table 1. Survey Response Averages for Fall 2024

| Statement # | Average Likert-scale response and standard deviations for CHEN 4316 | | | | Average Likert-scale response and standard deviation for GEEN 1201 | |
|---|---|---|---|---|---|---|
| | Pre-survey | Post-survey | | | Pre-survey | Post-survey |
| 1 | 4.75 ± 0.97 | 5.00 ± 0.0 | | 1 | 4.30 ± 1.42 | 4.73 ± 0.81 |
| 2 | 4.69 ± 0.98 | 5.00 ± 0.0 | | 2 | 4.23 ± 1.41 | 4.81 ± 0.78 |
| 3 | 4.69 ± 0.98 | 5.00 ± 0.0 | | 3 | 4.37 ± 1.30 | 4.73 ± 0.81 |
| 4 | 4.69 ± 0.98 | 5.00 ± 0.0 | | 4 | 4.40 ± 1.36 | 4.77 ± 0.80 |
| 5 | 4.75 ± 0.97 | 4.88 ± 0.33 | | 5 | 4.37 ± 1.28. | 4.77 ± 0.80 |
| average | 4.71 ± 0.98 | 4.98 ± 0.16 | | | 4.33 ± 1.35 | 4.76 ± 0.80 |

The scores for the in-class group exercise indicated a reasonable level of comprehension regarding the concepts posed in each exercise. The critical thinking question on the final exams had high responses (a score of 4 or higher out of possible 5 points) from 6 out of 17 students in the senior course and from 10 out of 30 students in the freshman course. These results indicate a direct impact regarding critical thinking for a significant fraction of the students in each course. Finally, the surveys for both courses displayed a moderate increase in student recognition of critical thinking and their interest in critical thinking as related to their future engineering career, when comparing the survey administered prior to the module presentation to the survey administered after the module presentation. However, the difference between the means of the pre-survey and post-survey Likert responses for both courses was not found to be significant when subjected to a paired t-test. This statistical result, in light of the clear difference in average values between pre-survey and post-survey of Table 1, indicates that a revision of the survey statements should be considered. In summary, these results indicate a positive impact of the critical thinking module on the student's ability to address technical challenges on group projects in both the senior level capstone engineering course and the freshman introduction to engineering course, although adjustment of the survey instrument is suggested for more statistically meaningful results.

## Conclusions and Future Work

Based upon the success in incorporating this module into two chemical engineering courses, and the positive results from student assignment and exam work, as well as the survey results, the instructor intends to continue including the module in subsequent offerings of these courses. The instructor realizes that the critical thinking lecture presented in these classes can be further refined to clarify the aspects of critical thinking described earlier, namely (a) clear and rational thinking; (b) understanding the logical connection between ideas; and (c) connections between abstract and the physical world. A more detailed assessment of the student use of critical thinking in their design projects will be developed. Institutionalization of the redesign will principally involve refining the critical thinking hands-on activities, as well as revising the survey evaluation of critical thinking student reflection at the end of the course.

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