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# Enhancing Critical Thinking in a First-Year Engineering Course using a Hands-On Study of Vectors

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# Enhancing Critical Thinking in a First-Year Engineering Course using a Hands-On Study of Vectors


## Abstract

This evidence-based practice paper describes development of a hands-on activity that was integrated within existing curriculum for first-year engineering students in an Introduction to Engineering course. Critical thinking instruction is a key component of this course and is demonstrated to students through instruction and application of the Paul-Elder (PE) critical thinking framework. In past years, students applied the framework primarily through a series of written assignments.

This year, the instructors aimed to enhance students' understanding of the PE framework and development of critical thinking skills through a collaborative team project investigating vectors. Students mapped out paths on campus using a tape measure and compass, then described their paths using vectors. They were asked to reflect critically on the results, considering sources of error in their measurements, and write a team report explicitly addressing elements from the PE framework.

Student surveys conducted at the end of the semester suggested a better student impression of critical thinking development as a result of the added vector assignment compared to previous years with only written assignments. A review of student reports revealed that, while the majority of students were adequate at applying at least some of the key critical thinking elements specific to this assignment, only a small percentage of them appeared to successfully conduct a thorough application of the PE framework. As a result of this work, several improvements to the course and assignment have been identified and will be implemented in future iterations of the curriculum.


## Introduction

All first-year engineering students at the University of Louisville are required to take an Introduction to Engineering course. This is a large enrollment course (in the fall of 2015, there were approximately 615 students in 18 sections) taught by two faculty members and four teaching assistants. Although only one credit hour, many topics are covered, including introductions to the different engineering disciplines, instruction in critical thinking, team building and communication, ethics, professionalism, and introduction to engineering design.

Critical thinking instruction, in particular, has been one area the instructors have aimed to improve and reinforce in each iteration of the course. Students in this course are provided explicit instruction in the Paul-Elder (PE) critical thinking framework (Figure 1).[1] The PE framework was adopted by the university to improve critical thinking skills for all undergraduates across the curriculum. In addition to explicit instruction of the PE framework in the Introduction to Engineering course, the PE framework is a critical component of other courses in the engineering curriculum. The framework highlights that good critical thinking involves identifying the *elements* of one's reasoning and assessing the quality of that reasoning using *standards*.

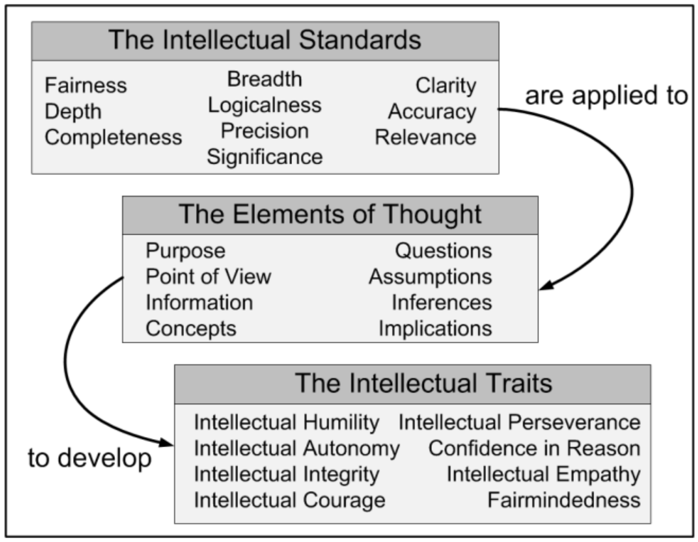


Figure 1. The Paul-Elder Framework of critical thinking.[1]

In past years, students applied the framework through analysis and evaluation of an engineering related article and were encouraged to use the framework in development of several written assignments.[2-3] However, student feedback indicated that their understanding and appreciation of the PE framework was mixed (roughly one-third of students found the framework useful in development of critical thinking, one-third felt that knowledge and application of the PE framework did not improve their critical thinking skills, and one-third remained neutral).[2] Thus in Fall 2015, faculty members sought ways to improve critical thinking instruction in the course.

Various instruction methods have proven effective in encouraging critical thinking in engineering students. In review of the literature, Cooney et al.[4] found two primary areas for best practices in critical thinking education: writing for reflection and problem-based learning. Similarly, Romkey and Cheng[5] highlighted interdisciplinary problems, open-ended problems and discussion, reflection, and active learning as effective techniques for critical thinking development. Despite the technique applied, several common themes emerge when researching effective development of critical thinking skills.[4-6]

1. Explicit instruction of critical thinking is important; assessment tools and frameworks can be used as a guide,
2. The instructor should model “good” critical thinking practice,
3. The instructor must provide ample opportunities for the students to practice critical thinking.

Furthermore, collaborative learning has been shown to increase depth of learning and the retention of knowledge.[7] It has been reported that students enjoy class more and are retained in their major when collaborative learning is utilized in the classroom. [7] As previous course activities related to critical thinking were primarily individual and writing-based, the instructors sought to develop a hands-on collaborative activity that would provide an opportunity for students to develop critical thinking skills in a more applied, project-based manner.

## Methods

*Critical Thinking Instruction*

Prior to the team vector project that is the focus of this paper, two 50 minute class periods were devoted to critical thinking instruction. In the first class, students were given a short lecture on critical thinking and the PE framework. Then students were asked to focus more specifically on the *elements* of the PE framework through a collaborative activity. In this activity, student teams were asked to analyze an engineering-related article by identifying and describing each of the elements within that article. The second class period focused on the *standards* of the PE framework. Student teams revisited the article they had discussed in the previous class, now to evaluate the quality of the reasoning by applying each of the PE intellectual standards. Finally, students were assigned an individual written reflection as homework, in which they were instructed to apply the PE elements and standards when considering their reasoning for pursuing a degree in engineering.

*Vector Mapping Project*

In order to reinforce the critical thinking concepts previously taught and provide an opportunity for students to apply the concepts in a more hands-on manner, students were assigned a team project in which they were to map out paths between two locations using vectors and evaluate their results. Students, grouped in teams of 3-5, were provided 'start' and 'stop' points at various locations throughout the engineering campus. Utilizing a tape measure and compass (to measure distance and change in direction), students were instructed to calculate vectors to map two different paths between their respective 'start' and 'stop' points. Students then analyzed and compared the two calculated paths (noting that the sum of the position and return vectors should theoretically equal zero) and reflected critically on the results. Conclusion of the project involved team-written reports in which students were required to explicitly address the PE framework elements of thought applied to their methodology, results and analysis.

Given that this is one of the first courses in the engineering curriculum, it was expected that many of the students had never written a technical (engineering) report. Thus, some instruction in technical writing was provided, and students were given the opportunity to receive formative feedback on their reports through peer assessment. Student teams swapped project reports and evaluated the reports (as a team) using an instructor-provided rubric based on the PE framework (Figure 2). In particular, this rubric asked students to evaluate whether the authors' purpose, key questions, concepts, assumptions, and conclusions were clearly stated, accurate, and sufficiently explained. In addition to identifying whether the report met described criteria (exemplary, satisfactory, or needs improvement) for each element, students were instructed to provide comments justifying their rating. Students were then able to revise their reports using the peer feedback prior to submission to the instructor.

| Category | Exemplary | Satisfactory | Needs Improvement |
|---|---|---|---|
| **Purpose** | Demonstrates a clear understanding of the assignment's purpose | Demonstrates an understanding of the assignment's purpose | Is not completely clear about the purpose of the assignment |
| **Key Questions** | Accurately identifies the core issues; appreciates the depth and breadth of the problem; demonstrates fair-mindedness toward problem | Identifies the core issues but may not fully explore their depth and breadth; demonstrates fair-mindedness | Fails to clearly define the issue or problem; has trouble maintaining a fair-minded approach toward the problem |
| **Concepts** | Identifies and accurately explains relevant key concepts | Identifies and explains/uses the key concepts, but not with depth and precision | Misunderstands key concepts or ignores relevant concepts altogether |
| **Assumptions** | Accurately identifies assumptions; makes assumptions that are consistent, reasonable, valid | Identifies assumptions; makes valid assumptions | Fails to identify assumptions or fails to clearly explain them, or the assumptions identified are irrelevant and/or invalid |
| **Inferences, Conclusions** | Conclusions are thoughtful, logical and supported by evidence and reason; Makes deep rather than superficial inferences | Conclusions are logical and supported by evidence and reason; makes valid inferences | Makes illogical, inconsistent inferences; Uses superficial, simplistic, or irrelevant reasons and unjustified claims |
| **Writing and Organization** | Information is presented in a logical way, easy to follow with no spelling or grammatical errors. Sections are clearly outlined with headings. | Key elements are presented in a logical order. Only a few spelling or grammatical errors. | Report is unorganized and difficult to follow. Spelling or grammatical errors are distracting to the reader. |

Figure 2. Rubric for peer assessment of vector project reports based on application of the Paul-Elder critical thinking framework.

*Assessment*

To evaluate the effectiveness of the vector project in meeting the stated goals and improving student learning related to critical thinking, student reports were evaluated to assess understanding of the PE critical thinking framework using the defined *elements* below. For the vector project, most of the elements were applicable; the following were expected to be used the most in the students' assignment:

- **Purpose**: The primary purpose of this assignment was to promote student application of the PE framework with respect to a more field-based, hands-on exercise (more reflective of engineering practice). The purpose was stated in the assignment problem statement handed out to students prior to activity commencement.
- **Questions**: What questions needed to be addressed to successfully execute the given task? Did application of this element simplify any procedures? Determination of team member roles would also fall under this element.

- **Concepts**: How was existing student knowledge of physics, vectors, measurements, applied to establish methodology for measuring and calculating vectors?
- **Assumptions**: For this scenario, assumptions would be primarily applicable to *expected results*. Researchers were also interested to see if any students made note of presuppositions that had to be modified as a result of the exercise.
- **Inferences**: This is perhaps the most important element for field-based work since inferences (i.e. conclusions or interpretations) is the element that most often promotes effective troubleshooting. There should be discrepancies between theoretical and experimental results. How well did students address all of the factors that could be the source of error? The depth (one of the PE intellectual *standards*) of this application was especially noted by the research team.

Additionally, reports were scored using a holistic engineering critical thinking rubric[4] (based on the PE framework) for an overall assessment of critical thinking ability (Figure 3). This rubric has been used previously in the course and in other studies to evaluate critical thinking in written artifacts,[2,8] and thus was used as a measure to compare critical thinking outcomes from the vector projects to assignments from previous semesters.

Students' perceptions of critical thinking skill development were assessed by a survey provided at the end of the semester. Students were assured that their answers on the survey were anonymous. Results were compared to those from the previous (Fall 2014) year to determine whether there were improvements in students' appreciation of the PE framework. Students from Fall 2014 were not exposed to the vector assignment, but did have the same instruction of the PE critical thinking framework with two lectures and two written reflections.

## Results & Discussion

### *End-of-Semester Survey Results*

Results for questions pertaining to critical thinking development from the student surveys are shown for 2014 (Figure 4) and 2015 (Figure 5). Questions 1 (Q1) and 2 (Q2) are identical for both the 2014 and 2015 surveys. The vector mapping project was added to course curriculum in 2015, hence the additional third question (Q3) specific to this assignment is shown in Figure 5. Since Q1 and Q2 are quite analogous, aggregates for these two questions were calculated by summing overall negative responses ("Strongly Disagree" + "Disagree") and overall positive responses ("Agree" + "Strongly Agree") for both 2014 and 2015. This resulted in aggregates of 28.7% negative and 35.3% positive in 2014, and 30.3% negative and 38.5% positive in 2015. Negligible discernment is present between these two aggregates as 2015 had a slight increase in both negative (+1.6%) and positive (+3.2%) responses over 2014. Yet 2015 results for Q3 shows a decrease in negative responses versus the aggregates for both 2014 (-2.4%) and 2015 (-4.0%) in addition to an increase in positive responses for both (+9.9% vs. the 2014 aggregate and +6.7% vs. the 2015 aggregate).

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. Articulations insignificant or illogical implications and consequences that are not supported by evidence. |
| 1 | Unclear purpose that does not include questions. Inaccurate, incomplete information that is not supported by evidence. Incomplete presentation that ignores relevant assumptions and points of view. Fails to recognize or generates invalid implications and consequences based on irrelevant evidence. |

Figure 3. Holistic rubric used to evaluate critical thinking ability.[8]

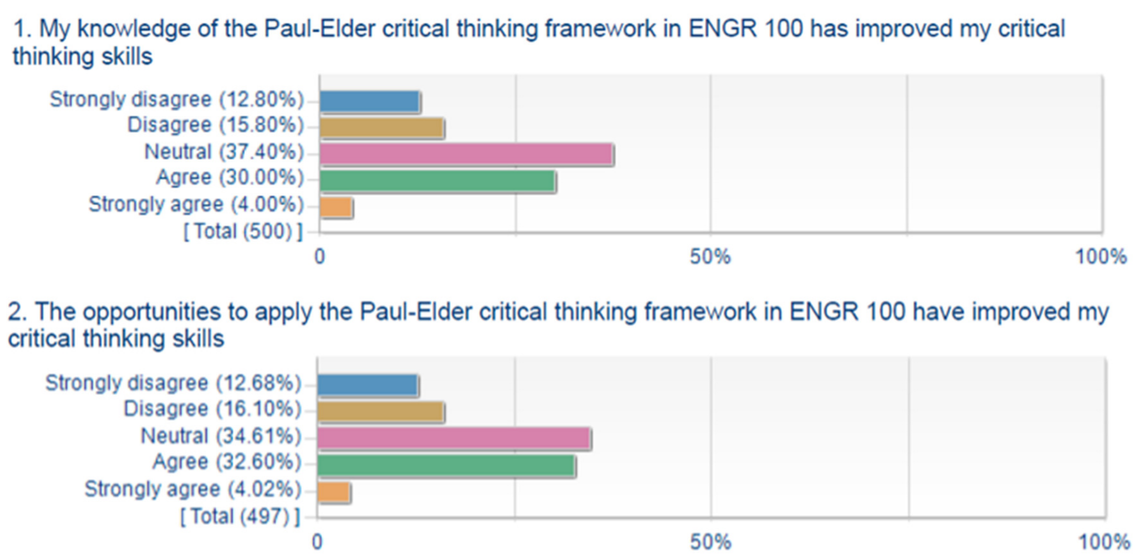


Figure 4. Student survey results for questions pertaining to critical thinking development for the Fall 2014 course.

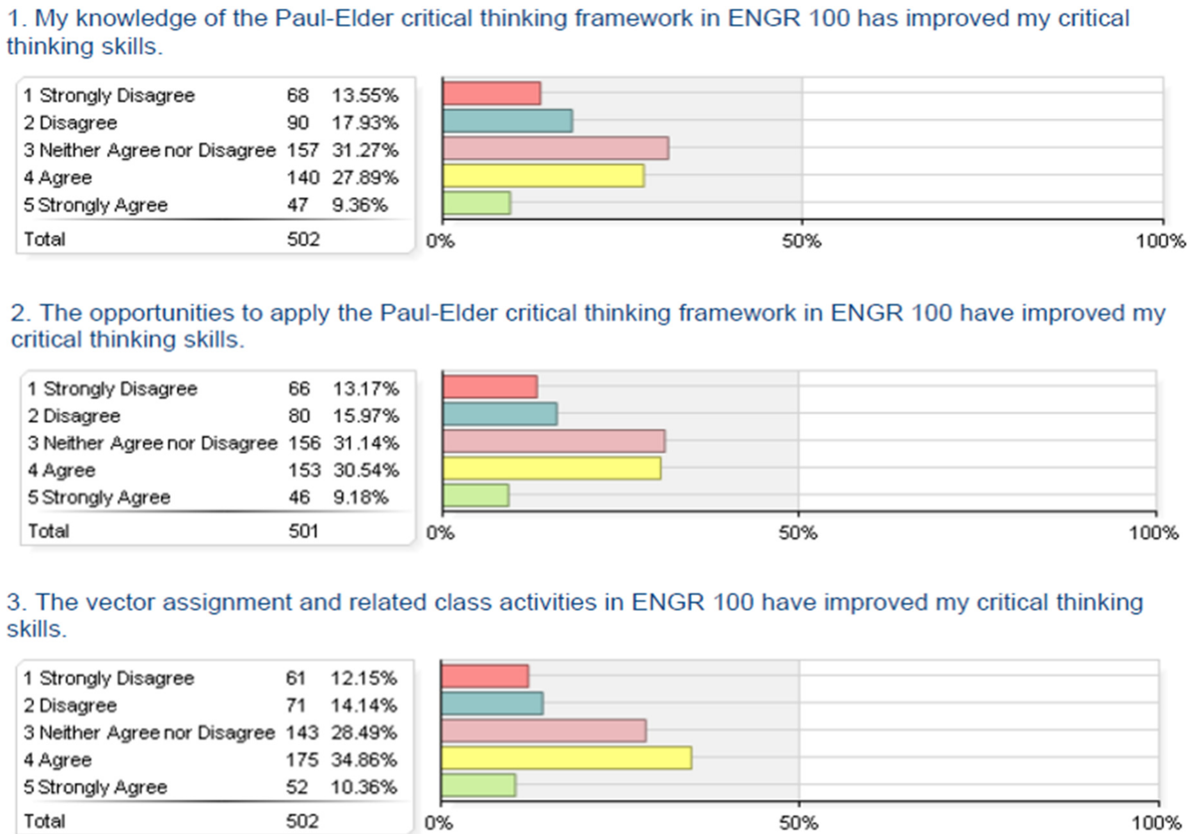


Figure 5. Student survey results for questions pertaining to critical thinking development for the Fall 2015 course.

*Assessment of Team Reports*

Collected team reports were assessed by course instructors and a subset of reports (n=23) were evaluated and scored, based solely on critical thinking merit, using the holistic rubric shown in Figure 3. The average score for evaluated reports was 2.3 with a standard deviation of 0.6. The score on the vector project reports was higher than that of written assignments in previous semesters (in which averages ranged from 1.7-2.1) suggesting improvements in the quality of critical thinking and application of the PE framework with the added vector project. However, caution should be used when comparing these critical thinking scores as the evaluations were conducted by different instructors on different assignments with different students. Challenges assessing critical thinking uniformly by different evaluators and on different assignments have been described in a previous paper.[2]

The intent of these scores are to provide a quantitative, reflective measure of student ability to effectively apply *all* of the PE elements of thought (Figure 1) specific to the vector mapping project. Often times, not all of the PE elements are applicable to certain scenarios, and it was the student's responsibility to determine which elements were relevant.

Only a small percentage of the students' project reports were effectual in adequately applying *all* of the PE elements towards the project, and a few more were adequate in applying each of the five targeted elements stated above. Despite the fact that the **purpose** (element) of the exercise was provided in the problem statement, a handful of teams still failed to demonstrate understanding of this element. For example, one group identified the purpose as: "*…it takes a simple paper calculation and puts it into a real world scenario*." A couple of teams based project 'success' on accuracy (which instructors expected to be quite erroneous), failing to note and/or understand that successful application of critical thinking is what determines actual 'success' for this project.

For students that struggled with adequately addressing the **questions** element, it was typically due to the inability to distinguish between generalizations versus specificity. Examples of generalized questions include: "*Can we work efficiently as a team?*", "*Are we able to think analytically?*" and "*Can we use the given tools to accurately measure the vectors we chose?*" While these may certainly be important questions to be confident in, they are not questions relevant for accomplishing the specific task in hand. Instead, odds of successfully accomplishing objectives would be improved by asking: "*How* do we work efficiently as a team?", "*How* do we use the given tools to accurately measure the vectors we chose?"

Examples of inadequate **assumptions** included assuming that "*little to no human error*" occurred during the process. This suggests that the PE standards of sufficiency and logic were not applied to this element. Another example along these same lines is that in which a group assumed that "*the compass was level*" while measurements were being made. This is a criterion that can and should be *confirmed*, not assumed.

There are numerous potential sources of error present within this task, including but not limited to: human error, instrument uncertainty, changes in elevation (thus affecting measured distance in an assumed 2D plane), and failure to account for magnetic declination of the compass. For the most part, teams were able to identify a reasonable amount of these potential sources as part of their **conclusions**. Although, there were a limited number of teams that failed to identify any sources of error at all or claimed causes that were illogical – such as one group's claim that their single source of error in their calculations was due to round-off error.

It is important to note that, while most failed to conduct a thorough application of the PE elements, many of the teams acknowledged that this assignment effectively underlined the value in further developing their skills for utilizing the PE framework. Numerous teams noted that initial presuppositions had to be modified as a result of this exercise, such as instances in which students highlighted in their concluding remarks that their assumption that the magnitudes of measured departing and return paths would be equal were invalidated upon completion of the exercise. The best inferences – actually supported by this exercise – were those in which students concluded that theoretical and experimental results can be significantly different. Several teams also stated that, prior to learning about critical thinking and the PE framework, their group would have certainly commenced the exercise without developing a beneficial strategy.

Often times, students would identify a certain PE element that may be more suitably identified as one of the other elements. For example, one team associated their expected results with the questions element ("*What are our expected results*?") instead of the assumptions element. The most regular occurrence of this was associating inferences with assumptions, and circumstances such as this cannot be deemed as incorrect. For instance, instead of interpreting the uncertainty in compass measurements as a source of error (application of the inferences element), several teams "*assumed that the compass was accurate*" (application of the assumptions element). This is acceptable as long as there is a realization of the need to assess the implications of these assumptions. Scenarios such as these further highlight the importance of systematically applying *all* of the standards and elements to ensure thorough critical thinking.

Perhaps the toughest component of evaluating team reports was in distinguishing between intuitive perception(s) versus actual application of the PE framework. For nearly every team, if expected results were reported, the reasoning behind these expectations were rarely discussed. When it appeared that an element had been correctly applied, it was often times unclear if this was a result of actual application of the PE framework rather than instinctively addressed. This occurrence was most common when students were discussing their methodology (*Why* did you "*use two people to operate the compass*"? *Why* did you decide to "*create 90$^o$ segments for your vectors*"?) It is essential that students understand that application of the critical thinking standards also applies to communication.

**Conclusions / Future Improvements**

This paper describes implementation and assessment of a vector mapping project into the Introduction to Engineering course as a means to develop students' critical thinking and teamwork skills. Survey results suggest that less than half of students (~45%) found the project effective at helping them develop critical thinking skills, though there were small gains over previous iterations of the course prior to implementation of the vector project. This highlights that further refinement may be needed to improve students' understanding and recognition of critical thinking. Assessment of team reports provided valuable insight into specific aspects of the assignment where further instruction is necessary.

Several steps have been acknowledged as means to further enhance the vector mapping project and reinforce critical thinking application for the Fall 2016 course. After team reports have been turned in, course instructors should discuss the key PE elements applicable to this assignment, especially all potential sources of error in measurements and calculations. This would not only be beneficial to strengthening student understanding of the PE framework, but would also likely improve students' knowledge base. For example, during field work for this assignment, one team was observed making measurements while holding each end of the tape measure in the air. Consequently, a significant sag was present in middle of the tape measure thus resulting in improper measurement of the true distance. While this particular team was made aware of this error, it is not possible to observe every methodological step taken by every team. If students are not made aware of their mistakes, then they are unable to account for them in the future. Improving student awareness will improve capability to apply certain PE elements (such as **concepts**) in future uses of the PE framework. Another step taken will be requiring students to explicitly address, within their report, applications of the PE elements specific to the assignment. This should greatly assist evaluators in ascertaining use of common sense versus a thorough assessment of the PE elements.

It is pertinent to note that, upon completion of this assignment, the majority of students expressed the secondary benefit of greatly improved teamwork skills, and students also reported an improved understanding of the significance of teamwork in engineering. It is important that these same values are attributed to the development of critical thinking skills. Thinking critically in a structured manner (such as utilizing the PE framework) can be very frustrating for first-year students. In many instances during this assignment, critical thinking was ineffective because existing student understanding of concepts was lacking. Students need to be made aware that this is expected at this stage of their development, and that acquired knowledge is a fundamental component of critical thinking (especially for the **concepts**, **assumptions**, and **interpretation** elements). Therefore, as they continue to acquire knowledge along their academic and professional career, their ability to effectively think critically will improve accordingly. It is critical to convey to students that perseverance in developing these skills is crucial, and to assure them that, over time, mastering these skills will become 'second nature' and will have a strong, positive impact on their ability to make meaningful contributions to the engineering profession.

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