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Redesigning an Introductory Mechanics Course to Include Meaningful Design Experiences

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Abstract

The United States Air Force Academy (USAFA) is a commissioning source for the U.S. Air Force, and as such, it strives to provide each graduate a well-rounded undergraduate education, grounded in a Science, Technology, Engineering, and Math (STEM) curriculum, in addition to military officership training to help each student prepare to become a leader in the Air Force immediately following their graduation. Mechanical Engineering 220 – Fundamentals of Mechanics (ME 220) is one of many STEM courses that all students, both engineering and non-engineering majors, are required to take. The course focuses on statics and mechanics of materials. This course plays two key roles in the overall curriculum at the USAFA. It is a required, or core, course and is most often the second of five engineering courses that every student is required to take, usually during their sophomore year. It is also the foundational course for students pursuing a degree in Mechanical Engineering or in Civil and Environmental Engineering. In its role as a core course, ME 220 is expected to satisfy certain institutional learning outcomes, including how to apply engineering methods, especially design methodology. In the recent past, the course had fallen short in meeting several institutional outcomes. In a series of conversations and meetings, the department faculty and leadership specified the various deficiencies in the course with respect to meeting these outcomes, the most prominent of which was the lack of curriculum dedicated to teaching and practicing engineering design. To better achieve these outcomes, the course was redesigned during the summer of 2021. Three experimental sections of this course were taught to randomly assigned students during the Summer session and during the Fall semester of 2021. Ultimately, the new course design was fully adopted and was taught by 7 instructors to approximately 400 students in 17 sections during the Spring 2022 semester. With minor refinements to the course syllabus and project after the Spring 2022 semester, the content for ME 220 has stabilized and will continue to be taught with these meaningful design experiences. A critical piece of the redesign is a new final project that is centered on a design-build-test experience that is accessible to all students, no matter their background or intended major. In this paper we will briefly discuss the previous course and how it has been modified to better address the institutional outcomes. We collected survey data from the students where they self-assessed their abilities with respect to certain institutional outcomes before the semester started and after the course concluded. The data include responses from students who experienced the legacy course during the Fall 2021 semester, and these data will be compared to the responses from the students who experienced the new course during the Summer 2021, Fall 2021, and Spring 2022 semesters. The data show that student proficiencies remained the same for most institutional outcomes. One major highlight from the results is that student proficiency for the institutional outcome that targeted the understanding of prototyping increased more for students taking the redesigned course compared to students taking the legacy course.

Background & Motivation

The mission of the United States Air Force Academy (USAFA) is "to educate, train and inspire men and women to become officers of character motivated to lead the United States Air Force and Space Force in service to our Nation [1]." This mission sets the USAFA apart from most other institutions of higher learning. Contrast this statement with the Massachusetts Institute of Technology's mission statement: "to advance knowledge and educate students in science, technology, and other areas of scholarship that will best serve the nation and the world in the 21st century [2]," or Harvard's mission statement: "to educate the citizens and citizen-leaders for our society [3]." It is important to understand the USAFA's three-pronged mission to educate, train and inspire the students to become officers of character, because it provides additional context and motivation behind the curriculum that the institution requires.

The USAFA is a commissioning source for the U.S. Air Force, and as such, it strives to provide each graduate a well-rounded undergraduate education, emphasizing a Science, Technology, Engineering, and Mathematics (STEM) curriculum, in addition to military officership training. Each student must take a series of 34 academic courses beyond their major's courses to meet graduation requirements [4] (often called "general education" courses at other universities). This set of required courses is known as the core courses, because they have been identified as fundamental courses for officer development [4]. Among the core courses are five engineering courses. Mechanical Engineering 220 – Fundamentals of Mechanics (ME 220) is most often the second core engineering course, the first being an introductory computer science course, that every student will take before graduating, usually during their sophomore year [4]. It is also the foundational course for students who are pursuing a degree in Mechanical Engineering or Civil and Environmental Engineering. As one of the core engineering courses, ME 220 is expected to help satisfy certain institutional learning outcomes, primarily teaching students how to apply engineering problem-solving methods with an emphasis on design methodology [4]. An institution-wide review of the USAFA's student outcome pertaining to engineering, the Application of Engineering Problem-Solving Methods (AEM) outcome, determined that the four-year core engineering curriculum was not meeting certain criteria for this outcome [5]. Therefore, the Mechanical Engineering Department (DFME) initiated an effort to revise their core engineering course, ME 220. Numerous stakeholders, including, but not limited to, DFME leadership, ME 220 instructors, and students, were engaged in identifying potential improvements to the course's alignment with the aforementioned outcome. Following this initial analysis, the course was redesigned during the summer of 2021 to better achieve these outcomes, and three experimental sections of the new course were taught to 73 randomly assigned students during the Summer session and during the Fall semester of 2021.

DFME had several secondary motivations in revitalizing the ME 220 course. Two key pieces of information provide context for these secondary motivations. First, approximately 500 students, or 12.5% of the student body, are enrolled in the course in a given semester. Since the course is required for graduation, the students may be majoring in any discipline, from History, English, and Political Science, to Mechanical Engineering, Physics, and Biology. Second, the students must declare a major by the end of the first semester of their sophomore year. Therefore, if a student takes the course relatively early in their academic course of study, they may not have declared a major by the time they take ME 220. The department wanted to convince students that learning engineering principles would be valuable throughout their academic experience and beyond graduation, no matter their major or career aspirations. DFME also wanted to give students exposure to more facets of engineering beyond statics and mechanics of materials by incorporating some engineering design into the class. This was intended to pique student interest in the subject while some are still deciding on a major. The Department hoped to encourage more students to study engineering. Furthermore, the team anticipated that teaching the students innovation, critical thinking, and decision-making skills through the design lessons and project would also increase the course's relevance to the students. The engineering design experiences would naturally provide the students with more opportunities for hands-on, interactive, and fun course activities beyond what the legacy course offered. Some of these engaging course activities would allow students to test their newly acquired innovation knowledge and skills by designing, building, and testing physical prototypes, which was not part of the legacy course. Designing, building, and testing physical prototypes are central to the new course, because it helps address these secondary motivations by actively engaging students in engineering, while simultaneously satisfying the previously unmet institutional outcome.

USAFA Outcomes

There are nine overarching institutional learning outcomes at the USAFA [6]. These USAFA Outcomes consist of a "sophisticated combination of knowledge, skills, and responsibilities that [students] will need to succeed as airmen and citizens [6]." Of the nine USAFA Outcomes, USAFA leadership intends for ME 220 to contribute primarily to the Application of Engineering Problem-Solving Methods outcome. The course also inherently addresses the Critical Thinking (CT) outcome. Each outcome is further refined to specific proficiencies, which constitute detailed knowledge, skills, and responsibilities that each USAFA graduate is expected to acquire through the sum total of their student experience: their undergraduate education, military training and officer development, physical education and training, and character development [6]. Although there are many facets of a student's training throughout their four years at the USAFA, several of the institutional outcomes, such as the Application of Engineering Problem-Solving Methods outcome, depend primarily on the academic curriculum to attain proficiency. An example of a specific proficiency for this outcome is: "*Describe and apply the principles governing the performance and capabilities of aerospace vehicles and cyber systems, and their possible effects*. [6]" Classroom instruction and coursework is best suited to help students achieve this proficiency, as opposed to a military or physical training environment, for example. Therefore, the academic departments are primarily responsible for delivering a cohesive and comprehensive curriculum, composed of suitable courses, such as ME 220, to gain proficiencies in said outcomes. The white papers [6] that outline the institutional outcomes for the Application of Engineering Problem-Solving Methods and Critical Thinking outcomes and their respective proficiencies are included for reference in Appendices A-B. Table 1 summarizes the Application of Engineering Problem-Solving Methods outcome and its associated proficiencies.

Table 1: Application of Engineering Problem-Solving Methods Outcome Proficiencies

Fundamental Domain Knowledge	
Proficiency 1	Describe and apply the principles governing the performance and capabilities of aerospace vehicles and cyber systems, and their possible effects.
Proficiency 2	Describe and apply principles governing the performance, capabilities, and defense of USAF's critical communication, sensing, control, and physical infrastructure.
Problem-Solving Process	
Proficiency 3	Formulate a problem definition from an incongruous set of requirements and constraints.
Proficiency 4	Create a viable design using robust and accepted engineering principles that considers the entire product life cycle including CONOPS, operations, sustainment, and disposal.
Proficiency 5	Apply decision-making skills in time-critical situations to help lead to problem resolution and objectively determine a design solution from a set of design solutions which best meets a given set of requirements.
Proficiency 6	Develop physical and/or virtual prototypes using engineering tools which are tested to evaluate candidate designs, then apply the results back into the design process to develop improved design solutions, inform the decision making process, and improve the final product.
Proficiency 7	Evaluate test results and determine if a solution meets given requirements and draw conclusions.
Proficiency 8	After solving a problem, students will reflect to comprehend systematic problem solving processes and the relationship to continuous process improvement.

It is also important to note that the USAFA leadership expects ME 220 to specifically address the Application of Engineering Problem-Solving Methods outcome proficiencies 1, 2, 4, 5, and 7 (see Appendix A).

ME 220 Course Overview

Some familiarity with the legacy ME 220 course is needed to understand how the current course content was developed. ME 220 is, in essence, a statics and mechanics of material course. In the legacy course, 2-D particle equilibrium, rigid body equilibrium, structural analysis of trusses, frames, and machines, material properties, internal loads, normal stress due to axial loading and pure bending, combined loading, and shear stress due to direct shear and torsion were covered. Student learning was assessed with three exams, a final exam, and three projects. Students were submitted a reports for a tensile test laboratory and an eccentric combined loading laboratory. In addition, students coded cells in a spreadsheet template that was provided to assist them in specifying the material and cross-sectional dimensions for a new B-52 wing spar that met certain requirements under a given biaxial combined loading case. That final engineering design project, which primarily consisted of determining the specifications for a B-52 wing spar, also included a formal report explaining the process the students used to identify a wing spar that met the requirements. Though the course adequately covered the fundamental topics in statics and mechanics of materials, the course review team identified several weaknesses or gaps in content that generally fell into one of two categories: 1) Insufficient/incorrect course scaffolding and 2) Unmet institutional outcomes.

Insufficient Course Scaffolding

The legacy ME 220 course provided very little scaffolding to facilitate students' learning. Scaffolding provides a learning structure that prepares students to understand new concepts and to develop new proficiencies more easily by intentionally incorporating pedagogical building blocks to more complex concepts and proficiencies. On the other hand, fading deliberately removes the learning structure that is provided with scaffolding to help students become self-sufficient in their learning [7]. It is widely accepted that scaffolding and fading can help students succeed, particularly within and across engineering courses [8] [9]. The lack of scaffolding in ME 220 was most apparent when the students were asked to write a full report for the tensile test laboratory. Prior to this assignment, the students had not written any reports for the class, and thus had not received any direct feedback for technical writing, and though they were provided with a technical writing guide with an example report, there was no class time dedicated to discussing how to write a technical report. This may be the most glaring scaffolding omission in the legacy course; however, there were many other related deficits within the course.

Unmet Institutional Outcomes

The most concerning observation from the review of ME 220, however, was that, as a core course, it was not meeting the intended institutional outcome. The question posed to the reviewers was "What should ME 220 offer every student to help them progress in their development towards an officer of character?" While the course should continue to have a foundational statics and mechanics of materials content, equipping each student with additional skills necessary for a career as an Air Force officer was also desired. After careful consideration of the institutional outcomes, the Application of Engineering Problem-Solving Methods and Critical T outcomes in particular, the review team decided that intentionally introducing students to an engineering design process and giving them practice implementing that process to generate solutions to problems would help them achieve several proficiencies of the Application of Engineering Problem-Solving Methods outcome. Fundamentally, an engineering design process is a methodical approach to thinking critically, solving problems, and making decisions; all of which are skills that students are expected to develop as they prepare to become officers. In fact, many of the proficiencies of the institutional outcomes relate to such skills [6].

Engineering Design in the Legacy Course

The legacy course did not effectively teach engineering design. The final project required students to select a material and cross-section dimensions for a B-52 wing spar and write about the process they followed to generate a spar that would meet requirements. Nevertheless, the only design-related content delivered to the students was a portion of one classroom lesson on how to use a decision matrix. Therefore, their final reports were generally lacking any substantive discussion about how they arrived at an acceptable design for the wing spar. It was apparent the students often just manipulated numbers in the provided spreadsheet until a viable design emerged. Another critical shortcoming in the legacy course and the final project was that students did not get any experience with physical prototyping. Physical prototyping is a major step in an engineering design process and is specifically called for in the institutional outcomes. Proficiency #6 of the Application of Engineering Problem-Solving Methods outcome reads:

"*USAFA graduates will be able to develop physical and/or virtual prototypes using engineering tools which are tested to evaluate candidate designs, then apply the results back into the design process to develop improved design solutions, inform the decision making process, and improve the final product.* [4]"

One could argue that in the legacy B-52 wing spar project, the spreadsheet used to quickly analyze the mechanical and geometric properties of candidate wing spar designs was indeed a virtual prototype, but the students did not develop the spreadsheet. Furthermore, the Department of Mechanical Engineering at the Air Force Academy takes pride in its faculty members' and staff's expertise, its world-class Applied Mechanics Laboratory, and other relevant resources that facilitate prototyping and manufacturing (as is likely the case for most, if not all, Mechanical Engineering departments at other institutions). The state-of-the-art facilities, experienced faculty members, and expert lab technicians equip the department to address the Application of Engineering Problem-Solving Methods outcome proficiency for prototyping and testing. The fact that the legacy ME 220 course did not involve any sort of physical prototyping and testing was a major shortfall that the department wanted to address. The team reviewing ME 220 determined that purposefully training students to use an engineering design process and including a project that provided a prototyping and testing experience so that they could execute that design process would be the two major thrusts of the course overhaul. Therefore, the course syllabus was revamped, introducing new engineering design lessons and objectives that now make up 25% of the course. Furthermore, the course projects were modified to enhance and to assess students' learning of the design process.

Liebenberg and Mathews reported that a similar change in content for the introductory engineering course at the University of Pretoria was highly successful in meeting their course outcomes [10]. Many of their outcomes were similar to the USAFA Application of Engineering Problem-Solving Methods outcome proficiencies and aligned with DFME's motivation for revitalizing ME 220. Some of their outcomes included teaching students how to effectively work in engineering teams, increasing students' interest in and understanding of engineering, and demonstrating the value that the course would have in their future careers. Their introductory engineering course was restructured to focus on teaching and practicing innovation and included design-build experiences for first-year engineering students. Liebenberg and Mathews found that focusing student learning on innovation with theoretical and practical curricula and design-build experiences had significant positive results. The student surveys indicated an improvement over the old course in every outcome category [9]. ME 220 differs from the University of Pretoria's introductory engineering course in many ways, more importantly in the fact that all students must take ME 220, not just engineering students. Despite the differences, the course review team anticipated that incorporating engineering design and innovation topics into the course, coupled with opportunities for students to practice design and innovation, would increase student effectiveness as they worked in teams, generate more interest in engineering, and allow students to see how innovation principles will help them in their future, no matter their specific career tracks, all in addition to meeting previously unmet institutional outcomes.

New Course

Though the syllabus for the new course has had some minor adjustments over the past year and a half since the first experimental offering, the commitment to offer a statics and mechanics experience through a design methodology lens remains. The following discussion outlines the current course content. A standard semester-long course at the USAFA includes 40 lessons that are 53 minutes long. Out of the 40 legacy ME 220 lessons, 30 were left largely unchanged, however the instructors were tasked to ask the students questions about the problems they were solving and the answers they were calculating in the context of design methodology. For example, if the students were given a 2-D particle equilibrium problem where a weight was suspended by two cables, instead of just solving for the tensions in the cables, the instructors might ask the students a follow-up question such as, “If the cables are only rated to hold 50 lb, would either of the cables break?” A more advanced question that an instructor might pose would be, “If each cable can only hold 50 lb before breaking, what is the maximum weight that can be suspended using this cable configuration?” Thus, in the process of teaching statics, the instructors were also encouraging the students to develop a design mindset.

The remaining ten lessons were significantly modified to better align with the course objectives, often incorporating new topics. The first lesson of the semester, which was traditionally dedicated to introducing institutional policies and explaining the administration of the course, became a lesson that introduced the engineering design process with a hands-on exercise. The lesson involved walking the students through understanding a customer’s needs, individually generating ideas for a design that would satisfy the customer’s needs, collaborating as a small group on a final design, building a small-scale prototype, and finally testing the prototype. This exercise was intended to motivate the design content for the remainder of the semester and to engage students, excite them, and attract them to the engineering discipline on day one.

The course review team added five new lessons to the syllabus that teach an engineering design process and include activities that give the students practice with the process. These five lessons were based on the steps of the engineering design process that Mattson and Sorensen describe in *Fundamentals of Product Development*, namely Understand the Need, Explore Concepts, Define the Design, Test the Design, and Refine the Design [11]. These lessons correlated directly to several institutional outcomes by providing a foundation upon which the students can develop critical thinking, problem solving, and decision-making skills, while also familiarizing them with tools they can use to augment these skills. Additionally, these lessons are prerequisites for them to successfully complete the new course project and were designed to act as scaffolding, preparing them for future courses they will take.

Half of one lesson was dedicated to discussing team dynamics in an engineering context to equip the students to work effectively in teams to complete a group project. Half of another lesson was spent introducing technical writing skills.

One lesson was slightly modified from the previous course to provide more practice with certain concepts that students have historically found to be difficult to grasp. Another lesson was re-focused on giving students practice with designing structures for axial loading.

Finally, the course review team set aside two lessons for building and testing a physical prototype for the course's final project. These two lessons helped build the students' abilities in two critical institutional outcome proficiencies related to physical prototyping, bridging the gap present in the legacy course's final project which involved limited virtual prototyping. To accommodate all of these additional lessons and the final project, three lessons on the structural analysis of frames and machines and a lesson on biaxial combined loading were removed from the syllabus.

New Final Project

The new design-build-test (DBT) project was designed using the scenario that the students were engineers helping to design a deployable bridge for soldiers that could be airdropped as parts in a box and rapidly assembled in the field. The DBT project was divided into five phases that followed the course topics as they developed throughout the semester. The phases also aligned with and assessed several lesson objectives, especially the new engineering design objectives. Most significantly, the course project gave students the opportunity to engage in meaningful design experiences. Like the new syllabus, the course project has evolved slightly to better address student and instructor needs, but the core structure and then design focus of the DBT project have been maintained.

<u>Phase 1</u>

The first phase of the project was assigned after completing the rigid body equilibrium and external loads block of material. Students were presented with a 2-D schematic of a simply supported bridge that also had two suspension cables attached, as shown in Figure 1. The uniformly distributed load acting along the length of the bridge represented the weight of the bridge, and the larger rectangular distributed load represented the weight of a vehicle.

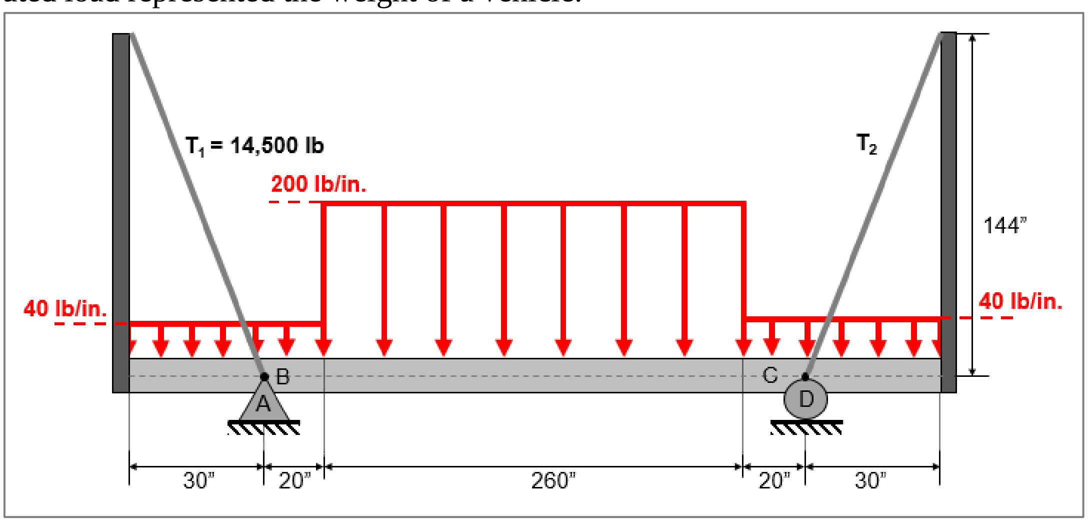

Figure 1: Simplified Loaded Bridge Schematic with External Supports

The students were tasked with finding the minimum tension in the right-hand cable that would ensure the roller support reaction at D would not exceed 26,000 pounds. The students also needed to calculate the resultant pin reaction, then, given the information in Table 1, they needed to select the most cost-effective option that would be adequate to support the loading on the pin.

Table 2: Pin Support Hardware Options

Part Number	**Pin Specification**	**Max Allowable Load before Pin Failure (lb)**	**Cost ($)**
1	Diameter = 0.31 in	8,002	$0.09
2	Diameter = 0.35 in	10,205	$0.12
3	Diameter = 0.41 in	14,008	$0.16
4	Diameter = 0.45 in	16,842	$0.19
5	Diameter = 0.51 in	21,634	$0.25

Phase 2

The second block of material focuses on axial loading. During this block, the students were assigned the second phase of the DBT project. The scenario for this phase was that the contractor for the bridge suspension cables needed the design team to decide which material to use for the suspension cables. The students performed a tensile test to identify an unknown material specimen sent from the contractor, based on its mechanical properties. The students were also given specifications and requirements for the suspension cables, shown in Tables 3 and 4, respectively. They had to determine whether a cable made of the material they tested, with the specifications in Table 3 would meet the requirements in Table 4.

Table 3: Bridge Suspension Cable Specifications

Max Expected Load (lb)	Diameter (in.)	Length (in.)
14,500	0.4	156

Table 4: Bridge Suspension Cable Requirements

Elongation (in.)	Weight (lb)	Factor of Safety against Yielding
≤ 0.3	≤ 14	≥ 1.5

Each team of students tested a different material. Built to the given specifications and loading condition, none of the materials that were tested in the tensile test laboratory would meet the requirements. This was intentional, because it created a meaningful design experience for the students. In the report for this phase of the project, the students needed to recommend a change to the specifications, namely the cable diameter, that would allow a cable made from the identified material to meet all of the requirements. It is important to note that the students were provided a template for this report and were instructed to write a full technical report detailing the laboratory and their analysis of the cable performance. This was part of the course scaffolding.

Phase 3

The next block of material discussed internal loads in the context of bending, so the third phase of the DBT project involved generating internal shear and bending moment diagrams for the bridge schematic from Figure 1 and identifying the location and magnitude of the maximum internal bending moment along the beam. Since the students had not been introduced to flexural stress or combined loading at this point in the semester, they were not asked to calculate the maximum stress experienced by the bridge, however they did assess whether the calculated maximum internal bending moment met the requirements shown in Table 5.

Table 5: DBT Phase 3 Bridge Requirements

Reaction Force of Roller Support (lb)	Reaction Force of Pin Support (lb)	Internal Bending Moment Anywhere Along the Bridge (in-kips)
≤ 26,000	≤ 14,225	≤ 2,250

Phases 4 & 5

Phases 4 and 5 consisted of designing and building a one-tenth scale bridge girder prototype out of balsa wood, testing it to failure, and writing a final report on the design-build-test project. For designing, building, and testing the prototype, the schematic of the bridge girder was simplified, omitting the suspension cables, and the weight on the bridge was scaled down as illustrated in Figure 2.

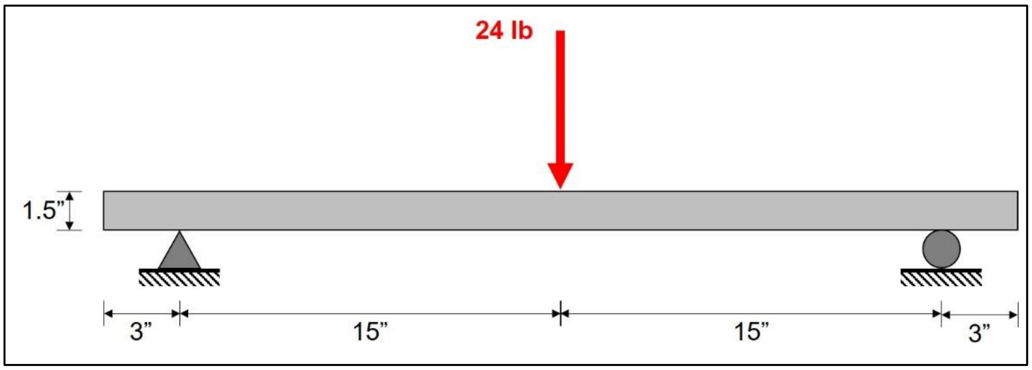

Figure 2: Scale Prototype Bridge Girder Loading Condition

The students had to design the prototype to meet certain specifications, shown in Table 6, and specific requirements, shown in Table 7.

Table 6: Bridge Girder Scale Prototype Specifications

Bridge Height (in.)	Bridge Width (in.)	Bridge Material
= 1.5	0.5 ≤ width ≤ 2	Balsa Wood

Table 7: Bridge Girder Scale Prototype Requirements

Span (in.)	Cost (USD)	Factor of Safety wrt Ultimate Strength	Max Deflection (in.)	Manufacturability (scale 1 to 5)
36	≤ $1.45	≥ 1.2	≤ 1.0	≤ 3

Each student produced at least one viable design, and each team of three to four students used a decision matrix to choose the best design from their group. The students had one class to build a prototype of the best design, and the next class they tested the prototype to failure. They weighed the prototypes, measured the maximum deflection at failure, and recorded the maximum weight their prototype held before failing to calculate the design's actual factor of safety. This project satisfied the institutional outcome for physical prototyping and allowed the students to practice all of the design principles that were presented throughout the course. Anecdotally, the first time the authors have heard students call ME 220 “fun” was during these two build and test lessons. This project also reinforced the lesson outcomes for flexural stress, second moment of area, beam deflection, downselection, and modeling and prototyping.

For the final report, student teams discussed their design and the prototyping process and reported their test results. This final report, in conjunction with designing, building, and testing the bridge girder prototype provided a culminating experience that assessed the students’ knowledge and understanding of the course material throughout the entire semester and delivered a hands-on, engaging, and meaningful design experience.

Results & Discussion

The new course was first taught during the in the Summer 2021 session with 16 randomly assigned students. These students voluntarily responded to a questionnaire at the start and the end of the course that had them self-assess their current abilities with respect to Application of Engineering Problem-Solving Methods and Critical Thinking outcome proficiencies. In the Fall 2021 semester, 57 randomly assigned students participated in two experimental sections of ME 220 that followed the new syllabus, including the new course project, while 530 students participated in the legacy ME 220 course. In the Fall 2021 semester 450 students voluntarily responded to the same outcome proficiency questionnaire at the beginning and the end of the semester. A blank questionnaire is included in Appendix C for reference. All self-assessment statements except the final one were derived from the proficiencies of the USAFA Outcomes for Application of Engineering Problem-Solving Methods and Critical Thinking (see Appendices A and B). The final question was included to capture the students’ self-efficacy in their learning development, which is a topic not specifically addressed in this paper. The initial and final questionnaires were identical to gauge a student’s self-assessed development in a given outcome proficiency from the beginning of the semester to the end. In the Spring 2022 semester, all seven instructors and 369 students participated in the new course with the new course projects. The same questionnaire was given to the students at the start and end of the semester, and 321 students responded.

The students responded to the questionnaire by selecting one of five responses to various statements. For example, one of the statements was, “I can create a basic, functional structural design of a simple static (i.e. non-moving) structure (e.g. a bridge, airplane wing, truss, building, etc.) using fundamental and accepted engineering principles.” This statement was derived directly from the USAFA Outcome for the Application of Engineering Problem-Solving Methods, Proficiency 4 (AEM P4): “USAFA graduates will be able to create a viable design using robust and accepted engineering principles that considers the entire product life cycle including CONOPS, operations, sustainment, and disposal.” The possible responses from the students were on a Likert scale ranging from the lowest proficiency level, “1 – I am unable to perform the task at this time / I have no idea what this means,” to the highest proficiency level, “5 – I would be completely able to perform the task for a test/project at this time.” The students’ responses were collected via a Google Form questionnaire and subsequently organized in a spreadsheet in Excel. The students’ names were masked by assigning each student a number. If a student chose to respond to both the initial and final questionnaires, their number with their associated responses was recorded on both questionnaires’ spreadsheets. The next step in data reduction involved calculating the difference, or delta, of each student's response from the initial to the final questionnaire. For example, if a given student (identified by their assigned number) indicated the lowest proficiency level, one out of five, to a statement at the start of the semester and then indicated the highest proficiency level, five out of five, to the same statement at the end of the semester, the delta was five minus one, or four. Thus, a larger delta suggested the student experienced a greater development of a given proficiency over the course of the semester.

The deltas were calculated for the students who were taught the legacy syllabus in the Fall 2021 semester, and those data were compared to the deltas for the students who were taught the new syllabus in the Spring 2022 semester. Figure 3 displays the average delta for statements 1 through 23. The Application of Engineering Problem-Solving Methods outcome proficiencies 1, 2, 4, 5, and 7 (see Appendix C) are outlined with blue boxes at the top of the figure, because, as previously mentioned, in the overall, institutional scaffolding of officer development, USAFA intends for ME 220 to specifically address these proficiencies. Therefore, the questionnaire results for these statements are of particular interest. Looking at Figure 3, it is evident that the average delta for every statement is greater for the new course. For 10 out of the 23 statements (43%), this difference is statistically significant. The statement numbers for these 10 statements are enclosed in a green circle on Figure 3.

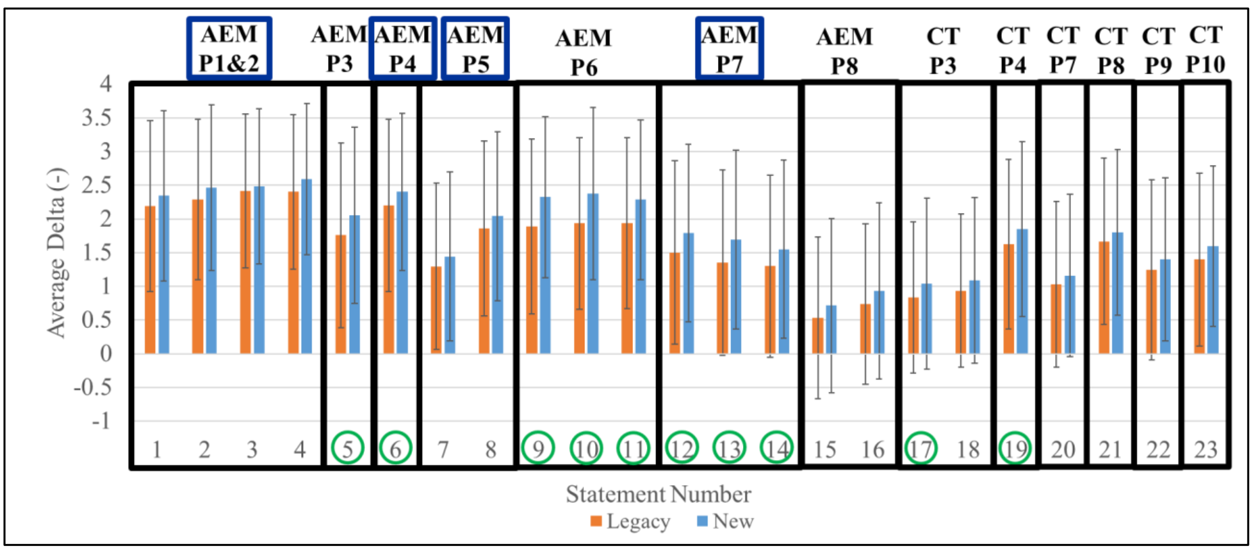

Figure 3: Average Delta from the Initial to Final ME 220 USAFA Outcome Questionnaire

The review team analyzed the difference between the legacy course and the new course delta data using a two-sample t-test assuming unequal variances with the null hypothesis stating that the difference between the mean delta for each data set was zero. For 10 out of the 23 statements, the t-tests showed that the null hypothesis must be rejected, suggesting that students improved more over the semester in those 10 skills when they were taught the new course than when they were taught the legacy course. The improved skills are related to proficiencies 3, 4, 6, and 7 of the Application of Engineering Problem-Solving Methods outcome and proficiencies 3 and 4 of the Critical Thinking outcome.

The course revitalization team set out to better align ME 220 with the USAFA Outcomes. With respect to Application of Engineering Problem-Solving Methods outcome proficiencies 1, 2, 4, 5, and 7 for which ME 220 has primary responsibility, the data suggest an improvement in 40% of the targeted proficiencies (i.e. proficiencies 4 and 7). The leadership for the Department of Mechanical Engineering was also interested in capitalizing on the department's strength in prototyping and testing, and the new course project engaged the students in designing, prototyping, and testing an original balsa wood bridge girder design. The Application of Engineering Problem-Solving Methods outcome proficiency that addresses prototyping and testing is proficiency 6. Figure 3 shows that students who were taught the new syllabus improved more in this proficiency over the legacy course. Figure 4 shows the percent difference between the average delta from the questionnaire results of the new course versus the legacy course in the 10 aforementioned statements/skills that showed significant improvement. The differences range from an 8.7% increase from on statement 6 ("I can create a basic, functional structural design of a simple static (i.e. non-moving) structure (e.g. a bridge, airplane wing, truss, building, etc.) using fundamental and accepted engineering principles. (Application of Engineering Problem-Solving Methods Outcome, Proficiency 4)") to a 22.3% improvement on statement 13 ("After conducting a test/experiment, I can evaluate the results (i.e. understand the significance and the relevant application of the data collected). (Application of Engineering Problem-Solving Methods Outcome, Proficiency 7)". These results are very positive and have informed the decision to continue teaching the new course for the foreseeable future.

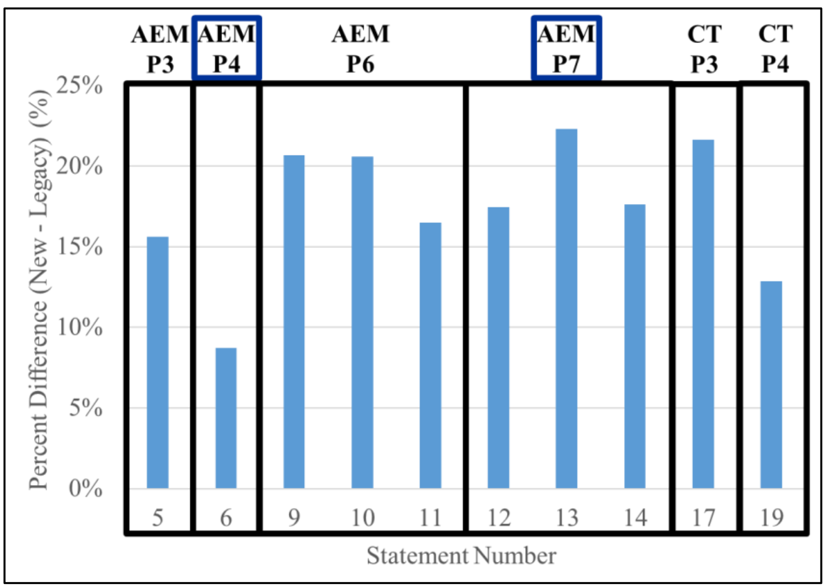

Figure 4: Percent Difference between New and Legacy Course Average Deltas

To further evaluate student performance, 41 out of 50 problems on the Final Exam remained the same from the Fall 2021 semester to the Spring 2022 semesters. The Final Exam in ME 220 was cumulative and consisted of 50 multiple-choice questions. Some questions were conceptual, though the majority required working out a statics or mechanics of materials problem. The review team compared the Final Exam results and found that students from the Fall 2021 semester performed better on average than students from the Spring 2022 semester. The average Final Exam score in Fall 2021 was 69.2% and in Spring 2022 the average was 66.3%. Since the exam is entirely multiple choice, with no potential for partial credit, this difference in exam score average suggests the average student in the Fall 2021 semester answered one or two more multiple-choice questions correctly (2% or 4% better) than the average student in the Spring 2022 semester. This difference was statistically significant, and the percent difference for Final Exam scores between semesters was 4.19%. Students from the Fall 2021 semester on average performed better on 14 problems (34.1%) of the 41 common Final Exam problems, while students from the Spring 2022 semester on average performed better on 4 problems (9.8%). There was no statistically significant difference between the students' performances in the two semesters on the remaining 23 problems. There was no clear commonality between the problems that the students performed better on in the Fall 2021 semester versus the Spring 2022 semester. Some of the problems the students did better on in the Fall 2021 semester required them to think about design, however some of the problems the students scored better on in the Spring 2022 semester required the same design mindset. The average incoming GPA of the students in the Fall 2021 semester was 6.18% higher than the average incoming GPA of the students in the Spring 2022 semester. The authors believe that this difference in average student incoming GPA might account for the 4.19% percent difference in average Final Exam scores. These data seem to be consistent with the students' self-assessment questionnaire data. The results of the questionnaire established that there was no significant difference between the new and legacy course with regards to the Application of Engineering Problem-Solving Methods outcome proficiencies 1 and 2. These two proficiencies have to do with describing and applying fundamental domain knowledge (i.e. the principles of statics and mechanics of materials). Due to the multiple-choice nature of the Final Exam, it principally assessed the students' fundamental domain knowledge, as opposed to their problem-solving and decision-making skills, which were primarily assessed in the course project. Since the project was significantly different between the new and legacy course, a comparison of student performance between the two semesters would not provide additional insight to gauge the impact of the changes made to the course.

Conclusions

The student proficiency self-assessment questionnaire suggested that the redesigned course helped students achieve institutional outcomes better than the legacy course. In the terms of the institutional outcomes, they improved in a "combination of knowledge, skills, and responsibilities that [students] will need to succeed as airmen and citizens [6]." The authors believe that the higher Final Exam scores in the Fall 2021 semester might be accounted for by the higher incoming GPA of the students during that semester. Overall, the data suggested that the new course addressed the relevant USAFA Outcomes better than the legacy course by introducing engineering design lessons and meaningful design experiences without sacrificing the core statics and mechanics of materials content. This design-focused approach can be implemented in any university's engineering curriculum to motivate students' learning, to develop their critical-thinking, problem-solving, and decision-making skills, and to help them understand how they can apply the concepts they are learning in their future careers.

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Appendix A – Application of Engineering Problem-Solving Methods Outcome White Paper [6]

APPLICATION OF ENGINEERING PROBLEM-SOLVING METHODS

Graduating students will recognize the engineering and technical challenges of the Air Force mission and the physical capabilities and limits within their assigned career fields and weapon systems. These officers need to not only be "operators," but to become problem solvers that use engineering principles to devise enhanced capabilities essential to achieving and maintaining Air Force dominance in air, space, and cyberspace. Proficiencies are organized into two broad categories:

- Fundamental Domain Knowledge (i.e., knowledge of basic engineering principles across a variety of physical domains relevant to Air Force missions in air, space, and cyberspace, and the infrastructure within which they operate).
- Problem-Solving Process (i.e., using a top-down, systematic problem-solving method, shown via italicized steps, to address the kind of ill-defined problems they will encounter across domains in their USAF careers).

USAFA GRADUATES WILL BE ABLE TO:

Fundamental Domain Knowledge

Proficiency 1: Describe and apply the principles governing the performance and capabilities of aerospace vehicles and cyber systems, and their possible effects.

Proficiency 2: Describe and apply principles governing the performance, capabilities, and defense of USAF's critical communication, sensing, control, and physical infrastructure.

Problem-Solving Process

Proficiency 3: Formulate a problem definition from an incongruous set of requirements and constraints.

Proficiency 4: Create a viable design using robust and accepted engineering principles that considers the entire product life cycle including CONOPS, operations, sustainment, and disposal.

Proficiency 5: Apply decision-making skills in time-critical situations to help lead to problem resolution and objectively determine a design solution from a set of design solutions which best meets a given set of requirements. (Includes Air Force CELO A2.7.2.1.1 listed under sub-competency A2.7.2: Decision Making).

Proficiency 6: Develop physical and/or virtual prototypes using engineering tools which are tested to evaluate candidate designs, then apply the results back into the design process to develop improved design solutions, inform the decision making process, and improve the final product.

Proficiency 7: Evaluate test results and determine if a solution meets given requirements and draw conclusions.

Proficiency 8: After solving a problem, students will reflect to comprehend systematic problem solving processes and the relationship to continuous process improvement. (Includes Air Force CELO A2.7.2.1.2 listed under sub-competency A2.7.2: Decision Making).

Appendix B – Critical Thinking Outcome White Paper [6]

CRITICAL THINKING

Upon graduation, our graduates will be required to identify and solve complex problems and effectively respond to situations they have not previously confronted. Acting responsibly in an ever-changing world of ill-defined problems requires critical thinking. At USAFA, critical thinking is defined as: The process of self-aware, informed, and reflective reasoning for problem-solving and decision-making even in the absence of ideal conditions. Cadets' critical thinking is developed in an intentional manner across the USAFA experience, promoting the use of appropriate critical thinking processes within a discipline or context.

USAFA GRADUATES WILL BE ABLE TO:[1]

Self-aware Reasoning

Proficiency 1: Describe their own assumptions and contexts.

Proficiency 2: Explain how their own assumptions and contexts influence approaches to problem solving and decision making.

Informed Reasoning

Proficiency 3: Identify relevant information that is needed to solve a problem or make an effective decision.

Reflective Reasoning

Proficiency 4: Identify the assumptions and contexts that underlie an argument.

Proficiency 5: Evaluate the strength of an argument in support of an idea or interpretation.

Proficiency 6: Propose alternative interpretations of information or observations.

Problem-solving and Decision Making

Proficiency 7: Identify issue(s) in need of solving.

Proficiency 8: Intentionally apply an appropriate process to develop solutions to an issue..

Proficiency 9: Assess the merit of multiple options in order to identify the best solution.

Proficiency 10: Explain how changes to assumptions or contexts alter the recommended solution.

[1] These proficiencies were modelled after the American Association of Colleges and Universities Essential Learning Outcomes www.aacu.org/leap/essential-learning-outcomes, the Foundation for Critical Thinking:

http://www.criticalthinking.org//, and Facione, PA (2015). Critical Thinking: What it is and why it counts. San Jose, CA: California Academic Press, http://www.insightassessment.com/Resources/Critical-Thinking-What-It-Is-andWhy-It-Counts

Appendix C – ME 220 USAFA Outcomes Initial/Final Questionnaire

Please select the answer that most accurately reflects your current abilities.

1. I can describe the fundamental principles governing the performance and capabilities of basic, static (i.e. non-moving) structures. (Application of Engineering Problem-Solving Methods Outcome, Proficiencies 1 & 2)

   1 – I am unable to perform the task at this time / I have no idea what this means
   2 – I could begin to perform the task but am quickly overwhelmed at this time
   3 – I could make progress toward performing the task but would fall well short of completing it at this time
   4 – I could almost completely perform the task at this time
   5 – I would be completely able to perform the task for a test/project at this time

2. I can apply the fundamental principles governing the performance and capabilities of basic, static (i.e. non-moving) structures to simplified, 2-D structures (e.g. bridges, airplane wings, trusses, buildings, etc.). (Application of Engineering Problem-Solving Methods Outcome, Proficiencies 1 & 2)

   1 – I am unable to perform the task at this time / I have no idea what this means
   2 – I could begin to perform the task but am quickly overwhelmed at this time
   3 – I could make progress toward performing the task but would fall well short of completing it at this time
   4 – I could almost completely perform the task at this time
   5 – I would be completely able to perform the task for a test/project at this time

3. I can describe the fundamental principles governing the strength/mechanics of materials (i.e. how different materials respond to external/internal loads/forces). (Application of Engineering Problem-Solving Methods Outcome, Proficiencies 1 & 2)

   1 – I am unable to perform the task at this time / I have no idea what this means
   2 – I could begin to perform the task but am quickly overwhelmed at this time
   3 – I could make progress toward performing the task but would fall well short of completing it at this time
   4 – I could almost completely perform the task at this time
   5 – I would be completely able to perform the task for a test/project at this time

4. I can apply the fundamental principles governing the strength/mechanics of materials (i.e. how different materials respond to external/internal loads/forces) when analyzing or designing a basic structure. (Application of Engineering Problem-Solving Methods Outcome, Proficiency 1 & 2)

   1 – I am unable to perform the task at this time / I have no idea what this means
   2 – I could begin to perform the task but am quickly overwhelmed at this time
   3 – I could make progress toward performing the task but would fall well short of completing it at this time
   4 – I could almost completely perform the task at this time
   5 – I would be completely able to perform the task for a test/project at this time

5. I can formulate a problem definition from a given set of requirements and constraints. (Application of Engineering Problem-Solving Methods Outcome, Proficiency 3)

   1 – I am unable to perform the task at this time / I have no idea what this means
   2 – I could begin to perform the task but am quickly overwhelmed at this time
   3 – I could make progress toward performing the task but would fall well short of completing it at this time
   4 – I could almost completely perform the task at this time
   5 – I would be completely able to perform the task for a test/project at this time

6. I can create a basic, functional structural design of a simple static (i.e. non-moving) structure (e.g. a bridge, airplane wing, truss, building, etc.) using fundamental and accepted engineering principles. (Application of Engineering Problem-Solving Methods Outcome, Proficiency 4)

   1 – I am unable to perform the task at this time / I have no idea what this means
   2 – I could begin to perform the task but am quickly overwhelmed at this time
   3 – I could make progress toward performing the task but would fall well short of completing it at this time
   4 – I could almost completely perform the task at this time
   5 – I would be completely able to perform the task for a test/project at this time

7. I can apply decision-making skills in time-critical situations to help lead to problem resolution. (Application of Engineering Problem-Solving Methods Outcome, Proficiency 5)

   1 – I am unable to perform the task at this time / I have no idea what this means
   2 – I could begin to perform the task but am quickly overwhelmed at this time
   3 – I could make progress toward performing the task but would fall well short of completing it at this time
   4 – I could almost completely perform the task at this time
   5 – I would be completely able to perform the task for a test/project at this time

8. I can objectively determine a design solution which best meets a given set of requirements from a set of design solutions (Application of Engineering Problem-Solving Methods Outcome, Proficiency 5)

   1 – I am unable to perform the task at this time / I have no idea what this means
   2 – I could begin to perform the task but am quickly overwhelmed at this time
   3 – I could make progress toward performing the task but would fall well short of completing it at this time
   4 – I could almost completely perform the task at this time
   5 – I would be completely able to perform the task for a test/project at this time

9. Using engineering tools, I can develop physical prototypes to be tested to evaluate preliminary designs. (Application of Engineering Problem-Solving Methods Outcome, Proficiency 6)

   1 – I am unable to perform the task at this time / I have no idea what this means
   2 – I could begin to perform the task but am quickly overwhelmed at this time
   3 – I could make progress toward performing the task but would fall well short of completing it at this time
   4 – I could almost completely perform the task at this time
   5 – I would be completely able to perform the task for a test/project at this time

10. Using engineering tools, I can develop virtual prototypes to be tested to evaluate preliminary designs. (Application of Engineering Problem-Solving Methods Outcome, Proficiency 6)

   1 – I am unable to perform the task at this time / I have no idea what this means
   2 – I could begin to perform the task but am quickly overwhelmed at this time
   3 – I could make progress toward performing the task but would fall well short of completing it at this time
   4 – I could almost completely perform the task at this time
   5 – I would be completely able to perform the task for a test/project at this time

11. I can apply the results from testing a prototype design back into the design process to develop improved design solutions, inform the decision making process, and improve the final product. (Application of Engineering Problem-Solving Methods Outcome, Proficiency 6)

   1 – I am unable to perform the task at this time / I have no idea what this means
   2 – I could begin to perform the task but am quickly overwhelmed at this time
   3 – I could make progress toward performing the task but would fall well short of completing it at this time
   4 – I could almost completely perform the task at this time
   5 – I would be completely able to perform the task for a test/project at this time

12. After conducting a test/experiment, I can evaluate the results (i.e. understand the significance and the relevant application of the data collected). (Application of Engineering Problem-Solving Methods Outcome, Proficiency 7)

    1 – I am unable to perform the task at this time / I have no idea what this means
    2 – I could begin to perform the task but am quickly overwhelmed at this time
    3 – I could make progress toward performing the task but would fall well short of completing it at this time
    4 – I could almost completely perform the task at this time
    5 – I would be completely able to perform the task for a test/project at this time

13. When evaluating test results, I can determine if a solution meets given requirements. (Application of Engineering Problem-Solving Methods Outcome, Proficiency 7)

    1 – I am unable to perform the task at this time / I have no idea what this means
    2 – I could begin to perform the task but am quickly overwhelmed at this time
    3 – I could make progress toward performing the task but would fall well short of completing it at this time
    4 – I could almost completely perform the task at this time
    5 – I would be completely able to perform the task for a test/project at this time

14. After evaluating test results, I can draw relevant conclusions. (Application of Engineering Problem-Solving Methods Outcome, Proficiency 7)

    1 – I am unable to perform the task at this time / I have no idea what this means
    2 – I could begin to perform the task but am quickly overwhelmed at this time
    3 – I could make progress toward performing the task but would fall well short of completing it at this time
    4 – I could almost completely perform the task at this time
    5 – I would be completely able to perform the task for a test/project at this time

15. After solving a problem, I reflect to comprehend the problem solving processes I utilized. (Application of Engineering Problem-Solving Methods Outcome, Proficiency 8)

    1 – I never engage in this behavior
    2 – I rarely engage in this behavior
    3 – I occasionally engage in this behavior
    4 – I often engage in this behavior
    5 – I always engage in this behavior

16. After solving a problem, I reflect to comprehend the relationship between the problem solving processes and continuous process improvement. (Application of Engineering Problem-Solving Methods Outcome, Proficiency 8)

    1 – I never engage in this behavior
    2 – I rarely engage in this behavior
    3 – I occasionally engage in this behavior
    4 – I often engage in this behavior
    5 – I always engage in this behavior

17. I can identify relevant information that is needed to solve a problem. (Critical Thinking Outcome, Proficiency 3)

    1 – I am unable to perform the task at this time / I have no idea what this means
    2 – I could begin to perform the task but am quickly overwhelmed at this time
    3 – I could make progress toward performing the task but would fall well short of completing it at this time
    4 – I could almost completely perform the task at this time
    5 – I would be completely able to perform the task for a test/project at this time

18. I can identify relevant information that is needed to make an effective decision. (Critical Thinking Outcome, Proficiency 3)

    1 – I am unable to perform the task at this time / I have no idea what this means
    2 – I could begin to perform the task but am quickly overwhelmed at this time
    3 – I could make progress toward performing the task but would fall well short of completing it at this time
    4 – I could almost completely perform the task at this time
    5 – I would be completely able to perform the task for a test/project at this time

19. I can identify the assumptions that govern an engineering problem. (Critical Thinking Outcome, Proficiency 4)

    1 – I am unable to perform the task at this time / I have no idea what this means
    2 – I could begin to perform the task but am quickly overwhelmed at this time
    3 – I could make progress toward performing the task but would fall well short of completing it at this time
    4 – I could almost completely perform the task at this time
    5 – I would be completely able to perform the task for a test/project at this time

20. I can identify issues in need of solving. (Critical Thinking Outcome, Proficiency 7)

    1 – I am unable to perform the task at this time / I have no idea what this means
    2 – I could begin to perform the task but am quickly overwhelmed at this time
    3 – I could make progress toward performing the task but would fall well short of completing it at this time
    4 – I could almost completely perform the task at this time
    5 – I would be completely able to perform the task for a test/project at this time

21. I can intentionally apply an appropriate process to develop solutions to an engineering problem. (Critical Thinking Outcome, Proficiency 8)

    1 – I am unable to perform the task at this time / I have no idea what this means
    2 – I could begin to perform the task but am quickly overwhelmed at this time
    3 – I could make progress toward performing the task but would fall well short of completing it at this time
    4 – I could almost completely perform the task at this time
    5 – I would be completely able to perform the task for a test/project at this time

22. I can assess the merit of multiple options in order to identify the best solution. (Critical Thinking Outcome, Proficiency 9)

    1 – I am unable to perform the task at this time / I have no idea what this means
    2 – I could begin to perform the task but am quickly overwhelmed at this time
    3 – I could make progress toward performing the task but would fall well short of completing it at this time
    4 – I could almost completely perform the task at this time
    5 – I would be completely able to perform the task for a test/project at this time

23. I can explain how changes to assumptions or contexts alter the recommended solution. (Critical Thinking Outcome, Proficiency 10)

    1 – I am unable to perform the task at this time / I have no idea what this means
    2 – I could begin to perform the task but am quickly overwhelmed at this time
    3 – I could make progress toward performing the task but would fall well short of completing it at this time
    4 – I could almost completely perform the task at this time
    5 – I would be completely able to perform the task for a test/project at this time

24. Initial: I believe that I can develop my understanding of course material so I can be successful in this course.
Final: I was able to develop my understanding of the course material to be successful in this course.

Strongly Disagree
Disagree
Somewhat Disagree
Somewhat Agree
Agree
Strongly Agree