# Comparing problem-solving across capstone design courses in chemical engineering

1st Eric Burkholder
*Department of Physics*
*Stanford University*
Stanford, United States
eburkhol@stanford.edu

2nd Carl Wieman
*Department of Physics, Graduate School of Education*
*Stanford University*
Stanford, United States

***Abstract*—Work in progress: Engineering graduates rank problem-solving as one of the most important skills they use in their careers. Despite the widely recognized importance of problem-solving, there is little evidence to suggest that we are teaching our students how to solve the complex problems they will encounter in their future careers. Part of the reason we lack such evidence is that almost no tools exist that measure meaningful dimensions of authentic problem-solving. We have developed an assessment of authentic problem-solving based on studies of how expert scientists and engineers solve problems. In the chemical engineering version of this assessment, students are asked to troubleshoot a flawed chemical process design; this requires them to make many of the same decisions that an expert engineer does when they solve real-world problems. In previous studies, we have validated the use of this assessment to measure differences between novice and more advanced students and to identify best practices for administering the assessment. In this study, we use the assessment to measure the problem-solving outcomes of two different versions of a capstone design course in chemical engineering: one that focuses on product design, and one on traditional plant design. We discuss preliminary results from two highly selected private universities in the United States. This work is providing valuable information as to the problem solving learning differences from different capstone design course experiences.**

***Index Terms*—capstone design, problem-solving**

## I. Introduction

Capstone design courses in undergraduate engineering curricula are intended to provide students with the experience of integrating the content knowledge they learn in various other courses and applying it to an authentic engineering design problem. Learning how to solve these "workplace problems" is an important outcome of undergraduate engineering education [1]. However, there is little evidence that students are learning to solve such problems successfully [2].

Much of the literature on problem-solving in physics [3]–[9] and engineering [1], [10], [11] education literature discusses the differences between experts and novices as they solve structured, textbook-style problems. While these are important contributions to our understanding of problem-solving, they do not address how experts or students solve complex, unstructured problems like the ones that practicing engineers and scientists encounter in the workplace. These "authentic" problems often have multiple solution methods, involve multiple forms of representation [12] and require higher order metacognitive skills to solve than do typical textbook problems.

Price et al. developed an empirical framework of problem-solving based on the decisions that expert scientists and engineers make as they solve authentic problems [13]. They find a consistent set of about 30 decisions made by experts across different scientific disciplines. These empirical findings agree with theory that suggests decision-making is key in solving open-ended design problems [14], [15]. Price et al. find that what allows experts to solve these complex problems is a predictive framework: a mental representation of the problem's key features and the relationships between these features. This framework allows the experts to identify important elements of the problem and eliminate unimportant elements, explain the mechanistic relationship between these problem elements, and conduct mental simulations of the problem and its outcomes. From this empirical framework of authentic problem-solving, we set out to develop an assessment for chemical engineering expertise that would measure meaningful aspects of the expert reasoning that Price et al. observe. This requires that each question the students answer in the assessment requires them to make one or more of the decisions that experts would while solving such a problem.

We developed an assessment containing 10 free-response questions concerning the design of a chemical process. The questions at the beginning are more generic (e.g. general feedback about feasibility) and progressively become more specific (e.g. safety concerns and optimization questions). In the first block of questions, students are given a process flow diagram that contains several errors and inefficiencies. They are asked to come up with a set of criteria on which the process will be evaluated, and then carry out that evaluation. They are also asked whether they think the process is physically feasible as illustrated, and if not, what modifications are necessary. In the second block they are given a process flow diagram where the errors have been corrected but the inefficiencies remain. They are asked what feedback they would give the person who designed the process, and whether the corrected process is optimized with respect to material and energy consumption. If they say the process is not optimized, they are asked what modifications are necessary to optimize it. In the third block

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of questions, participants are asked what information they would request concerning the process they are analyzing. They are then given a list of information with varying degrees of relevance and asked to rank the importance of each piece of information. Finally, they are asked what modifications they would make to the process based on the information given to them. In the fourth block of questions, participants are given an optimized process flow diagram and asked if they would accept this version of the process. They are also asked about any lingering safety concerns they have about the process, and finally, they are asked to summarize all the changes they would make to the original process. This assessment takes 60 minutes to complete and is administered online in Qualtrics.

We have previously conducted pilot studies assessing the validity of the assessment (including responses from experts in chemical process/product design) [16] and how it should be administered [17]. In this mixed-methods case study [18], we use the assessment to look for differences between different groups of students. Specifically, our research question is: are there differences in various facets of problem-solving between students who take different types of capstone design courses?

## II. Methods

We collected student responses to the problem-solving assessment from senior undergraduate students at two different universities; data were collected at the end of the capstone design course in chemical engineering. University 1 is a highly selective private research university in the northeastern U.S. At University 1, students took a capstone design course in concerning the design of a chemical process; students work in small groups on a semester-long feasibility study of a chemical process to produce either petrochemical or pharmaceutical products. Students work in a simulated corporate environment where the student teams of engineers make weekly progress reports to the faculty and TAs of the course. The feasibility study includes an analysis of product supply and demand, a complete process simulation, and a complete economic analysis including off-plot support facilities for the chemical process. This course is hereafter referred to as the "process design" course. We recruited 7 volunteers from this process design course to take the assessment. Volunteers received $25 in exchange for completing the assessment and were asked to think aloud as they solved the problem to better illuminate their reasoning processes.

University 2 is a highly selective private technical university in the southwestern U.S. At University 2, students take a capstone design course that focuses on chemical product design. Over the course of the semester, the students work (in teams) in the laboratory to develop a prototype of a chemical product. In addition, students develop a customer statement and technical requirements for their product, an informal market analysis, and an analysis of regulatory and safety issues. Students in this course were required to complete the problem-solving assessment for course credit. We received complete responses from all 8 students in the course. This course is hereafter referred to as the "product design" course.

We first assessed students' written responses as to what criteria they would use to evaluate the process. We compared students' responses with responses collected from 3 experts in chemical process design and assigned students a numerical score based on the fraction of the criteria they listed that were also listed by the experts. As a check on the consistency of students' reasoning, we also calculated the fraction of criteria that students later used to evaluate the process. We next coded students' responses for what information they requested. Similar to the criteria score, we assigned students a numerical score representing the fraction of the information that they requested that experts also cited in their responses. We also compared how students' rankings of various pieces of relevant information matched the expert responses, and again assigned students a score reflecting what fraction of their rankings matched the expert rankings. We also coded students' responses for whether they suggested concrete ways to use any of the information that was given to them and whether they misinterpreted any of the information that was given to them. Students received a score of 1 if they were able to suggest concrete uses of information, and zero otherwise.

We assessed the quality of the design that students produced over the course of the assessment. We counted the fraction of errors in the initial process that students noticed and the fraction of potential improvements that students identified. We noted whether students were able to identify that the original process schematic they were given would not function, and whether students accepted the optimized design at the end of the assessment. Students were given a point for each error and improvement. We also counted instances when students suggested a modification to the process that would make it less function less optimally, or when students made a flawed assumption about how the process functioned.

## III. Results

In Table I we report the average criteria identification and evaluation scores for both courses. We find that students in both courses demonstrate similar facility in identifying expert criteria to evaluate the process. There is reasonable agreement between the students and experts on what criteria should be used to evaluate the process, suggesting that students are learning to identify to the goals of the problem. Students are inconsistent in actually using these criteria to evaluate the process however – they only address 50-60% of their own criteria in evaluating the process. The difference between product design and process design students on this measure is not statistically significant (Mann-Whitney test, $p = 0.44$) [19], but the statistical power to identify these differences is limited by the small number of participants.

In general, we find that students in the product design course (University 2) are better at addressing the criteria they identify in evaluating their design. There is no correlation between identifying expert criteria and addressing these criteria in evaluating the design (Kendall's =0.098, $p = 0.58$).

In Table 2 we report the results of what information students requested and how they interpreted information given to them.

TABLE I

AVERAGE CRITERIA IDENTIFICATION AND EVALUATION SCORES FOR STUDENTS FROM BOTH COURSES. THE CRITERIA IDENTIFICATION SCORE IS THE PERCENTAGE OF CRITERIA IDENTIFIED BY STUDENTS THAT WERE ALSO IDENTIFIED BY EXPERTS. THE SECOND COLUMN, CRITERIA APPLIED TO PROCESS EVALUATION, IS THE PERCENTAGE OF TOTAL CRITERIA LISTED BY STUDENTS THAT THE STUDENTS LATER USED TO EVALUATE THE PROCESS.

| Course | Criteria Identification (%) | Criteria Applied to Process Evaluation (%) |
|---|---|---|
| Product Design (N = 8) | 63.5 | 63.5 |
| Process Design (N = 7) | 69.8 | 49.3 |

More than 50% of the information that students requested about the process was also requested by experts. However, when asked to rank the importance of information given to them, students showed less agreement with experts (38.5% - 45.1%). The difference in information ranking between the two courses is not statistically significant (Mann-Whitney test, p = 0.23), although neither is very close to experts. Some of the students were able to suggest modifications to the process based on the information given to them (3 students in the product design course, 5 in the process design course). These suggestions almost always reflected ways to handle the extremely corrosive chlorine gas that is produced in the process. Only one student in each course misinterpreted any of the information that was given to them.

There is no apparent relationship between students' ability to identify important features of the problem (Information Ranking Score) and whether or not they are able to suggest a concrete way to use this information (Kendall's =0.027, p = 0.90).

We see substantial differences between the two courses on metrics related to the quality of the design that students produce (Table 3). Students in the product design course identified 20.8% of the errors in the original process and 18.8% of the potential improvements, whereas students in the process design course were able to identify 71.4% of the errors and 46.4% of the improvements. Both differences are significant at the p = 0.05 level (Mann-Whitney test). We find that students who failed to notice any errors in the design also failed to notice any improvements in the design. There is a moderate correlation between the number of errors that students noticed and the number of improvements that they suggested (=0.43, p = 0.03 [19]).

Most students were able to identify that the original process given to them would not function (5 of 8 in product design, 6 of 7 in process design), and all but one of the students recognized that the optimized process given to them at the end was superior to the designs they had seen previously. Two of the students in the process design course arrived at the optimized solution before being shown the diagram for it. Four students in the product design course suggested changes to the process that would have made it function less optimally, such as removing one of the reactors, which would greatly reduce the yield of the product due to the chemical equilibrium of the reactions. Three students in the product design course also made a bad assumption in analyzing the process. The most common flawed assumption was that the chemical reactions the process was based on could not occur in parallel.

Two of the three errors in the original design were fatal flaws that would cause the process not to function as indicated on the diagram—one was a mass accumulation loop and the other was a missing separator that would have led to a contaminated product stream. All but one of the students who noticed these errors were able to correctly identify that the original process was not physically feasible. Both of the students who failed to identify either error said the process was feasible.

## IV. DISCUSSION AND CONCLUSIONS

There are several notable trends in the data. First, we see large differences between the process design and product design students on metrics related to the quality of the design that they produce. Product design students only notice about 20% of the errors and potential improvements in the design. Process design students notice most of the errors (71.4%) and about half (46.4%) of the potential improvements to the design. It seems plausible that process design students score higher on these metrics because they receive significantly more practice in designing chemical processes than students in product design. Despite this extra practice, the process design students are far from experts in identifying ways to improve the process.

Notably, most students in both courses were still able to identify (1) that the first process would not function and (2) that the final process diagram they were shown was superior to those they had seen before. We hypothesize that most students were able to correctly make these decisions because they were based on a small number of criteria. For (1), there were two fatal flaws in the original process, either of which students could have noticed to identify that the process would not function. For (2), there was essentially a single criterion required to make this decision – whether or not students noticed that the process diagram accomplished the specified goals with a substantially smaller number of units.

Other changes to the process, such as improvements to the design, involved much more complex decisions in which more criteria needed to be considered, such as efficiency of material consumption, efficiency of energy usage, yield of chemical reactions, etc. – and often deciding on the value of a change to the process would involve considering multiple criteria at the same time. Thus, it is unsurprising that students had more difficulty making decisions about changes to the process. It also makes sense that product design students, who have less exposure to the content knowledge required to make these decisions, would perform worse on these metrics.

Students in both courses are somewhat proficient in identifying the criteria on which the process should be evaluated (63.5% of the criteria cited by product design students were cited by experts, and 69.3 of the criteria cited by process

TABLE II
SCORES RELATED TO WHAT INFORMATION STUDENTS REQUESTED, HOW THEY RANKED INFORMATION GIVEN TO THEM, AND HOW THEY USED AND INTERPRETED THAT INFORMATION.

| Course | Information Request Score (%) | Information Ranking Score (%) | Suggested Concrete Ways to Use Info | Misinterpreted Information Given |
|---|---|---|---|---|
| Product Design (N = 8) | 52.1 | 38.5 | 3 | 1 |
| Process Design (N = 7) | 57.1 | 45.1 | 5 | 1 |

TABLE III
SCORES RELATED TO THE QUALITY OF THE DESIGN THAT STUDENTS PRODUCED OVER THE COURSE OF THE ASSESSMENT. COLUMN 1 LISTS THE AVERAGE PERCENTAGE OF ERRORS STUDENTS NOTICED IN THE ORIGINAL DESIGN AND COLUMN 2 LISTS THE AVERAGE PERCENTAGE OF IMPROVEMENTS STUDENTS SUGGESTED TO THE DESIGN.

| Course | Errors Noted in Design (%) | Improvements Suggested (%) |
|---|---|---|
| Product Design (N = 8) | 20.8 | 18.8 |
| Process Design (N = 7) | 71.4 | 46.4 |

design students were cited by experts). This reflects a particular set of content knowledge that chemical engineers should develop over the course of the curriculum – e.g. that processes should take safety and environmental impacts into account, or that the yield of product is an important determining factor in the economic viability of the process. However, students were not as good at actually applying the criteria they identify. The students in the product design course may be somewhat better at applying these criteria to evaluate the process. We hypothesize that this is due to a difference in instruction. Students in the product design course engage in deliberate practice with identifying goals and constraints of a problem, and then using those goals/constraints to evaluate their products. In the process design course, students spend less time explicitly thinking about how their process will be evaluated, and they do less self-evaluation of their progress.

All the students are poor at deciding what information is important/relevant, a key decision skill that experts use while solving problems. About 50% of the information students request is also requested by experts, and only about 40% of the information that students deem most important is deemed important by experts. Almost all students have no trouble interpreting the information given to them, but students are less adept at using the information to make modifications to the process. Students in the process design course are better at suggesting process modifications based on information given to them, which is likely due to their having more practice doing this in their coursework.

This reflects a weakness in students' predictive frameworks – they are unable to use information to make predictions about how the process will function. Given the consistency within this data, we expect that students are generally better at recognizing important features and information than they are at applying this information like experts do. Indeed, in Bloom's taxonomy, applying information is seen as a higher-order cognitive skill than identifying information [20]. We expect that this is because students do not have practice applying important features and information in problem-solving and therefore do not have a robust predictive framework that guides the use of this knowledge.

These preliminary results suggest that there are some differences in various aspects of problem-solving that students are learning in different capstone design courses, but that the differences can be understood in terms of what activities and decisions they practice in the respective courses. Our results suggest that the problem-solving students learn in the capstone design course may be highly contextualized—students in process design are learning specific content knowledge required to design processes, but not how to identify important information for solving problems, or using design criteria to evaluate the quality of the process. Students in product design are better at using design criteria to evaluate the process, but less adept at suggesting modifications to the process based on information given.

This work was conducted with a quite limited sample. In an ongoing study we are looking in more depth at the differences between students in product design and process design courses at University 1. Students will take the problem-solving assessment as a pre- and post-test so that we can identify population differences between the two courses and directly measure their learning of the expert problem solving skills covered with this assessment. The outcomes of that study will be very useful for thinking about the chemical engineering curriculum design.

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