2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering
Education for 130 Years
Paper ID #40075

Enhancing Effectiveness and Inclusivity of Introductory, Project-Based ME Courses: A Cognitive Psychology Approach

Mr. Frederic-Charles Krynen, Stanford University

Fred Krynen is a Ph.D. candidate in Mechanical Engineering at Stanford University. Under the guidance of Professor Carl Wieman, Professor Shima Salehi, and Professor Sheri Sheppard, his research focuses on teaching methods as they apply to introductory university-level mechanical design courses. He is focused on measuring these methods' impact on performance, retention and on the students' sense of belonging in the physical space they occupy while learning, and in the field of engineering. Previously, he worked as a Chef for eleven years in fine dining restaurants in five countries. In 2014, he returned to school to earn his GED, attended Mt Hood Community College in Gresham, Oregon and transferred to Stanford University in 2016. He holds a BS and a MS, both in Mechanical Engineering from Stanford University.

Prof. Carl E. Wieman

Enhancing effectiveness and inclusivity of introductory ME courses: A cognitive psychology approach

Fred Krynen, Carl Wieman, Shima Salehi

Abstract

Introductory mechanical design courses can either be invigorating and inspiring experiences or they can be alienating and intimidating depending on students' prior experience with design. This study explores cognitive psychology-based methods to teach mechanical engineering design courses effectively and inclusively to a diverse body of students regardless of their backgrounds. Therein, we investigated the effects of a course redesign that implemented deliberate practice and preparation for future learning. As a result of this theory-driven redesign, we observed significant improvements in individual problem-solving practices by evaluating student-produced artifacts. These artifacts were elements of the course final projects, called photo essays, which describe and justify students' prototyping efforts and the decisions they made during a four-week period in which they design and build a physical device—a candy dispenser in the control course and a stamping machine in the intervention course. A set of metrics of performance were compared with those of students in the control offering prior to the redesign of the course.

Introduction

In 2015, Stanford University's Bachelor of Science in Mechanical Engineering (BSME) curriculum underwent significant restructuring [1]. The program was altered to be comprised of a set of core classes and a set of concentrations in which students could choose to specialize. In the process, ME102 - Foundations of Product Realization was created. An introductory course to the relevant fields, ME 102 introduces students to new spaces (a prototyping lab and machine shop), new machines and software (e.g. 3D printers, laser cutters, CAD), and formally introduces the design process.

We know that success or failure in introductory courses plays a major part in students leaving STEM [2]. Previous studies have also shown that success in introductory STEM courses is primarily determined by students' incoming levels of preparation. Further, incoming preparation and the quality of the high school a student attended are heavily correlated [3]–[7]. Unfortunately, demographic patterns affect students' access to higher-quality high schools. Hence, demographics can play a large role in how students experience their first foray into engineering through courses like ME 102 [8]. If such courses are not carefully designed, they can pose a significant challenge to pursuing engineering fields, particularly for less prepared students who are more likely to be marginalized due to inequities in the educational system.

In an effort to address incoming preparation discrepancies, we implemented a redesign of ME102 over the AY 21-22 as shown in figure 1 by (1) redefining and categorizing the course learning goals (Summer '21), (2) developing and piloting measuring tools to assess the effectiveness of the changes proposed (Summer '21, Fall '21, Winter '22), (3) using cognitive psychology-based teaching methods to develop more effective and inclusive course activities (Fall '21, Winter '22), (4) piloting the changes (Spring '22, Summer '22) and (5) analyzing the difference in the pre- and post-intervention measures (Fall '22, Winter '23).

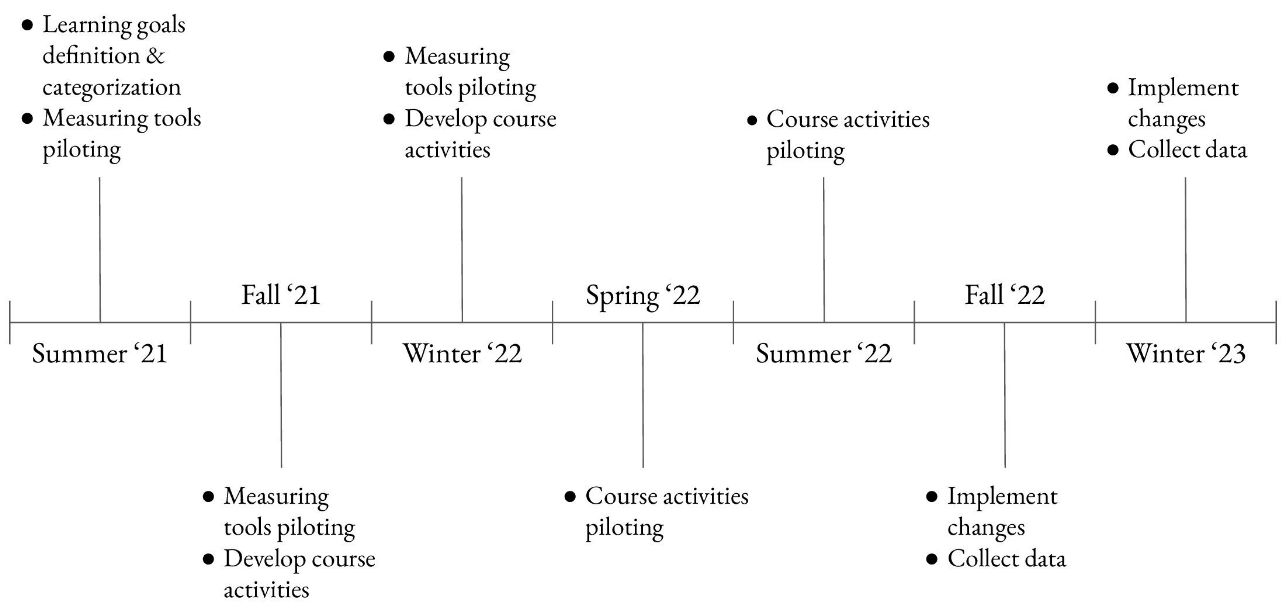

Figure 1: Timeline of the course redesign

Theoretical Framework

The theoretical framework for this course redesign stems from two seminal theories of cognitive psychology[9]–[11]: deliberate practice (DP), and preparation for future learning (PFL) [12]. DP theory, founded by Ericsson [13], delineates the general process of developing expertise in many different fields (e.g. sports, music, physics). PFL further offers a particular instructional design for DP and shows how a prior learning activity that prepares the learner can enhance learning from future instructor-led lectures.

For this study, PFL learning activities are given to students as small group activities in workshops in advance of corresponding lectures. These workshop activities are designed to be novel to not advantage better-prepared students due to similarity with previous courses and to be authentic (i.e. “real world” problems) to engage students regardless of their background or experience level. The activities are comprised of students in small groups completing a worksheet on a problem defined by the week’s learning goals. During these workshops, the instructional team engages students to share ideas, reflect on progress, and explore the problem and solution spaces further by providing just-in-time feedback. The subsequent lecture, then, expands on the workshop experience and formally presents the week’s learning goal(s).

The impact of this course redesign is measured by analyzing and systematically scoring students’ final project deliverables in the course. The scoring rubric, which we describe later, used for this study is based on the four mechanical design practices derived from Salehi’s STEM problem-solving practices [14].

Methods

As we outlined in the paper we submitted to ASEE in 2022 [15], the Fall and Winter offerings of the ’21-’22 academic year were used as the control condition for this study (see figure 2). The Spring offering of that academic year was the pilot for the developed intervention, and the ’22-’23 Fall offering of the course, with further refinements, served as the experiment condition.

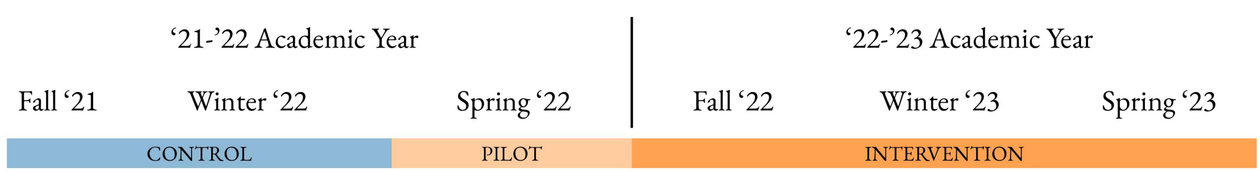

Figure 2: Timeline of the study

How DP and PFL are incorporated into the course

The original version of the course content was mainly composed of slide-based lectures and homework assignments. In the first step of the course redesign, we revised the course learning goals. We defined a complete set of learning goals based on the previous material. We then categorized these learning goals in a hierarchical manner with respect to the dependency of one on the next, with an overarching weekly learning goal consisting of a set of dependent sub-goals.

For the PFL design, we developed small group activities, based on the above goals, to be done in workshops. These activities were designed to present students with challenging and context-appropriate exercises, and to create a need for students to further learn about a phenomenon through instructor-led lectures. These activities were submitted and graded for completeness only. The workshop activities provided students an opportunity to (1) experience a new concept in a low-stake, non-threatening environment, (2) share their prior knowledge with fellow group members, and (3) make their best attempt, discuss and get feedback from the rest of their group. The workshop session happened five days before the instructor-led lecture where the topic was formally introduced. During lecture, there were frequent pauses when students were encouraged to discuss the content with their neighbors—such as Think-Pair-Share activities[16]—and to engage with the week's learning goals. At the end of the lecture, homework was assigned with less defined and more ambiguous problems than the ones in workshop or lecture. This allowed students to further develop and practice the targeted learning goals.

The tenets of deliberate practice theory were implemented in this course design as follows:

1. **Divide the targeted expertise into sub-learning goals:**
   Assessable learning goals were derived and hierarchically organized from course content.
2. **Design corresponding learning activities appropriate for students' incoming preparation:**
   Workshop activities, Think-Pair-Share activities, and homework exercises were created to increase the challenge presented to students as they developed the appropriate skill level.
3. **Provide learners with timely, specific, and tailored feedback on how to improve their performance in these activities:**
   The instructional team's presence in workshop, the group nature of the activities, office hours, and the common use of Slack provided support to students.
4. **Provide learners with the opportunity to incorporate the received feedback:**
   Every learning goal was interwoven into the class to be practiced multiple times.

The project in the intervention offering, which we describe later, incorporated all of the learning goals covered in the course. The course structure provided students with additional opportunities to practice the skills and incorporate feedback at another higher level of sophistication with less scaffolding and direction each time.

Differences between the pilot and the intervention offerings

The ASEE community provided valuable feedback when we presented the designed intervention for the course at the 2022 Minneapolis conference. Then, the need for a CA to meet for an hour each week with groups of four students raised concerns from ASEE members about the feasibility of this intervention being adopted outside of Stanford University.

In order to address these concerns and reduce the resource intensity of the intervention, these CA meetings were replaced with the above-mentioned weekly workshop sessions for the whole class. These workshops had 60 students with 2 CAs. The one-and-a-half-hour workshop session had four-student groups completing a worksheet at their own pace. The workshop sessions used similar learning activities as the previous coaching sessions (specifically targeted & authentic problems based on well-defined hierarchical learning goals). This revision in the course redesign reduced CA involvement in the course by 80%—from 15 CA-hours per week to 3 CA-hours per week.

Additionally, while students in the intervention offering performed significantly better than those in the control offering of the course, it is worth noting that the final project in the intervention offering—the universal stamping machine—was significantly more difficult to design and build than the one in the control offering—the candy dispenser. This is mainly due to the following factors: (1) The candy dispenser, by WI '22, had been the final project for the course for five consecutive terms and it was evident that designs from prior terms were being shared. On the other hand, FA '22 was the first term the stamping machine was featured as a final project. (2) In addition to the sharing of prior designs from past students, the teaching team in the control offering of the course had a lot of experience with candy machines, having seen many working and failing versions, and therefore was able to provide better more insightful feedback than the teaching team in the intervention offering. And (3), simply speaking, the candy dispenser's requirements were much easier to fulfill than those of the stamping machine—the stamping machine needed to be universal to the class's stamp assembly, the inkpad needed to be shielded and not removed, and the business card needed to be indexed for repeatable, accurate stamping.

Final Projects

The final projects for both offerings were composed of two deliverables, a physical device/prototype, and documentation presenting the student's design process.

Physical Devices

The final project was chosen to provide a fun design activity. The project for the control offerings was to design and build a candy dispenser. The project for the intervention offering was to design and build a universal stamping machine. The instructional team used the following requirements to select the final project. The project was to design and build a device that would:

- Be complex enough to require multiple rounds of physical prototyping
- Provide opportunities for students to prototype testable subsystems
- Integrate at least two mechanical subsystems
- Require the use of CAD skills
- Require the use of laser cutting and 3D printing
- Require the use of rotary motion and use of a provided spring
- Require the use and proper integration of mechanical hardware such as fasteners, shafts, and bushings.
- Have a testable & binary (pass/fail) use-case.

Once completed, students demonstrated their final projects' functionality for evaluation by the instructional team.

Photo essay

In addition to demonstrating their physical device's functionality, students had to submit their documentation in the form of a ”photo essay”. This compilation of 20 - 25 slides accounts for 70% of the final project's grade—21% of their final grade in the course. The photo essay, a stand-alone document, should concisely communicate the students' design process from start to finish and provide justification for the decisions made by students. In keeping with the course's ethos, students were encouraged to show both what they did and what they opted not to do, justifying their decisions throughout. The required elements of the photo essay were as follows:

- Cover Page
- Context for the project
- Inspiration/Benchmarking
- Concept Sketches
- Ranking/Decision Tree
- Physical Prototyping
- Driver questions and metrics for success
- Building and testing
- Test results
- CAD Screenshots
- Exploded view of the CAD assembly
- Bill of materials
- Reflection

Analysis

For analysis of the candy dispenser project in the control offering, we focused on scoring two critical subsystems: (1) the parsing mechanism (SS1)—which separated one artificial candy from the rest, and (2) the funnel—or hopper (SS2). For analysis of the stamping machine project in the intervention offering we also focused on scoring two critical subsystems: (1) the rotation-to-translation mechanism (SS1) used to actuate the device, and (2) the stamp receptacle (SS2), which had to be compatible with a stamp assembly common to the class. These subsystems were scored based on students' quality of performance in the mechanical design practices derived from Salehi's STEM problem-solving practices[14], as shown in figure 3. Given the complexity of each of the subsystems, more weight was given to the SS1s than to SS2s in the scoring rubric (see calculation below). This was consistent with the level of detail provided by students in their photo essays.

For SS1, the scoring rubric was based on the questions shown in figure 4.

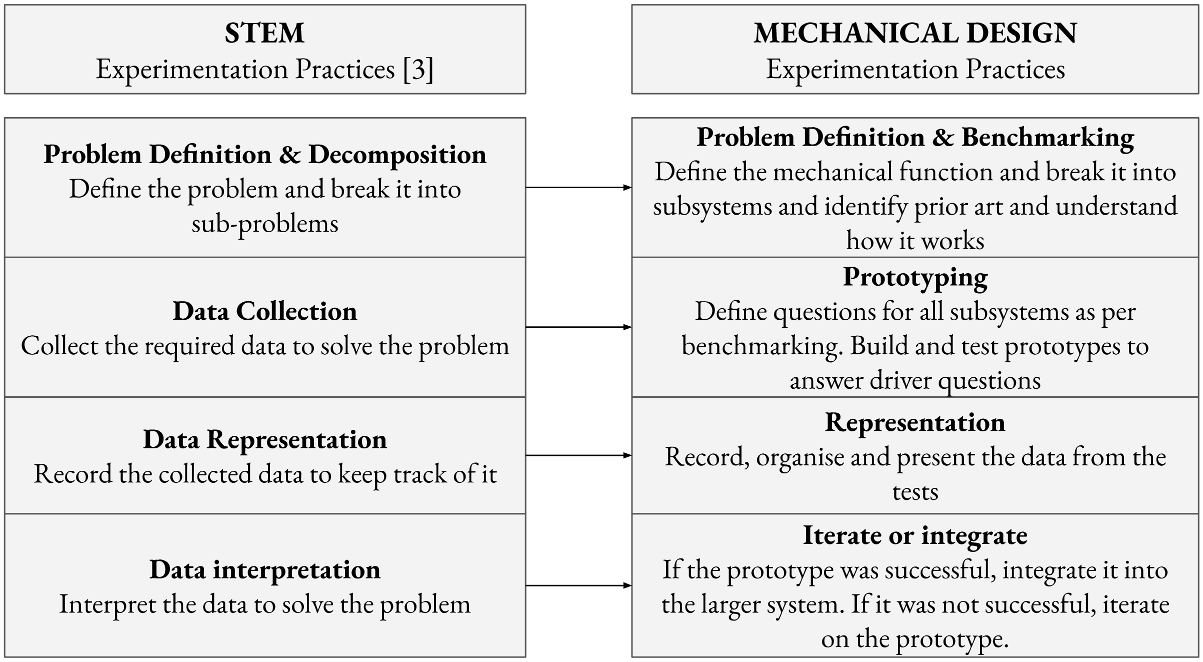

Figure 3: Mechanical design practices mapping of Salehi's experimentation practices

P1	**Problem Definition & Benchmarking**	Q1. Was a search of relevant prior art done? Q2. Was a known mechanism studied and understood? Q3. Were subsystems prototyped individually?`
P2	**Prototyping**	Q4. Were the prototypes driven by a specific question? Q5. Was the prototype built in a way to facilitate testing? Q6. Was the prototype built in an efficient way?
P3	**Representation**	Q7. Were the test results shown and well organized?
P4	**Iterate or integrate**	Q8. Were the subsystems methodically tested once integrated?

Figure 4: Questions used to evaluate SS1s as they relate to individual mechanical design practices

The questions in figure 4 were scored with the following rubric based on the students' representations in their photo essays:

			SCORE		
			0	**1**	**2**
P1	**Q1.**	Was a search of relevant prior art done?	No	Prior art is out of context	Prior art in situ
	Q2.	Was a known mechanism studied and understood?	No	Inaccurate reasoning & understanding	Accurate reasoning & understanding
	Q3.	Were subsystems prototyped individually?	No	Some subsystems	All subsystems
P2	**Q4.**	Were the prototypes driven by a specific question?	No	Driver question is binary	Driver question is non-binary
	Q5.	Was the prototype built in a way to facilitate testing?	No	Testing not included into the prototype	Testing included into the prototype
	Q6.	Was the prototype built in an efficient way?	No	Somewhat efficient	Very efficient
P3	**Q7.**	Were the test results shown and well organized?	No	Shown & Not organized	Shown & Organized
P4	**Q8.**	Were the subsystems tested once integrated?	No	Only tested once fully integrated	Tested as they are integrated

Figure 5: Detailed rubric used to calculate student score on SS1

A score based on each practice was calculated for SS1.

$$Score_{P1} = \frac{(Q1+Q2+Q3)}{3} \qquad Score_{P2} = \frac{(Q4+Q5+Q6)}{3}$$

$$Score_{P3} = Q7 \qquad Score_{P4} = Q8$$

$$Score_{SS1} = Score_{P1} + Score_{P2} + Score_{P3} + Score_{P4}$$

The SS2s were scored more simply with an overall score, as follows:

- 0 for not implemented
- 1 for implemented successfully without supporting documentation or poorly prototyped
- 2 for implemented successfully and well prototyped & documented

To compute a student's overall problem-solving score, the SS1 score was added to the SS2 score and scaled to a maximum of 100. The final score gave a measure of a student's problem-solving ability.

$$Score_{total} = (Score_{SS1} + Score_{SS2}) \times 10$$

The score was derived not from the quality of the final product but rather from the documentation provided by the student via their photo essay. This is important to note for three reasons:

1. Students coming from more privileged backgrounds may already be familiar with the tools and processes introduced in this class. While making a candy dispenser or stamping machine using those processes may be new to them, it would not be as daunting as for other—less experienced—students.
2. Documenting the process enabled the teaching staff to analyze how wasteful or efficient a student was in prototyping and making their device as opposed to solely looking at the final outcome.
3. Mechanical design is primarily a team exercise, and learning to effectively communicate and justify design decisions is a crucial part of becoming an engineer.

Results

This study investigated the effects of our intervention on teaching problem-solving skills in an introductory-level mechanical design course. Specifically, we examined whether students benefited from our incorporation of the theories of deliberate practice and preparation for future learning into the curriculum. We evaluated whether the students who took part in the intervention offering performed better on the course final project than those who did not. We found that students in the intervention offering performed significantly better than those in the control offering, as shown in figure 6 below, as measured by their problem-solving scores ($\beta = 1.10$, $SE = 0.25$, $t = 4.5$, $p < 0.0001$).

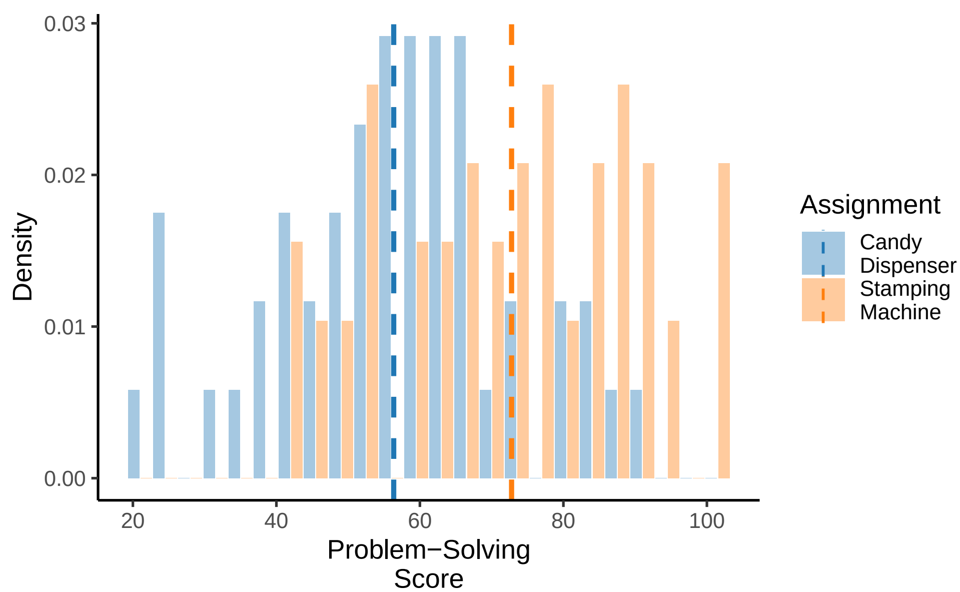

Figure 6: The distribution of problem-solving scores on the final projects across the two offerings. Dashed lines show median scores.

Students in the intervention offering were given low-stakes opportunities to practice both the actual skills (e.g., prototyping focused on answering a driver question with a plan to test and report findings based on pre-determined metrics for success) and the skill of documenting their process and representing their findings.

For example, in the first week of the house project, the midterm project of the intervention offering, students were asked to document their process when prototyping laser-cut, friction-fit walls as part of their homework. The instruction for this deliverable was brief: ”The documentation (3-6 pages) should help the instructional team understand your process”, and students were given a list of required elements (context, inspiration, prototyping plan, test results). This gave students a low-stake opportunity to provide their best attempt as to what good documentation might look like. The next week, their documentation was shared in workshop. In that session, students filled out a scaffolded feedback sheet to evaluate individual elements of the documentation. Students first gave feedback to every other student in their group and then provided feedback to the members of another group. This workshop session took place in advance of an instructor-led lecture on documentation.

At the end of the house project (a week later), students created a more complete (12-15 pages) photo essay for the project. Two weeks later, the workshop session was used as another feedback session, this time looking at the completed house photo essays. The session followed the same outline but this time every group was given one of four ”exemplary” photo essays (chosen by the instructional team from the set of essays submitted). The fact that it was exemplary was not shared explicitly with the students but they were asked to evaluate and provide feedback on it. This raised the students’ standards as to what a good photo essay looks like per deliberate practice theory.

The improvements we observed were evident not only in the overall problem-solving score for the final project but also at the individual practice level. Specifically, students in the intervention offering showed greater improvement in the areas of prototyping and documentation, when compared to students in the control offering as illustrated in figure 7.

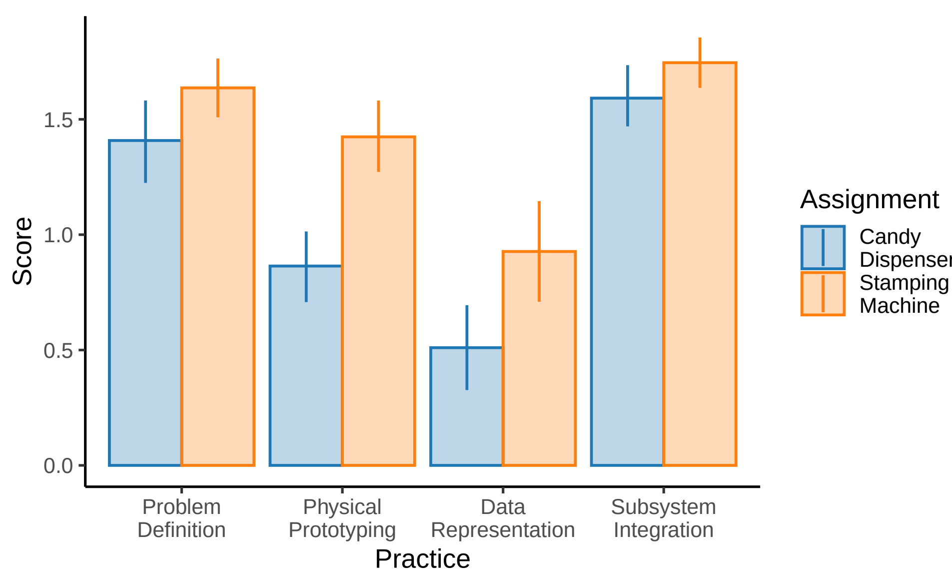

Figure 7: Scoring weights based on practices. Lines represent standard errors.

We attribute the significant improvements observed in physical prototyping ($W = 660.5$, $p < 0.001$, $Cohen's\ d\ effect\ size = 0.98$) and data representation ($W = 979.5$, $p = 0.009$, $Cohen's\ d\ effect\ size = 0.54$) to the changes implemented: our approach emphasized these practices supported by the incorporation of feedback, incremental complexity of activities and assignments focused on well-defined learning goals, and the evaluation of contrasting cases when providing feedback to other students.

We found less improvement in problem definition ($W = 1057$, $p = 0.042$, $Cohen's\ d\ effect\ size = 0.40$) and subsystem integration ($W = 1140$, $p = 0.099$, $Cohen's\ d\ effect\ size = 0.33$). This can be explained by the nature of the projects. In both courses, elements of the problem-solving practices had to be simplified by the instructional team for students to solve the challenge in time. These simplifications primarily occurred in the problem definition and subsystem integration practices. For example, the prompt of the stamping machine required the mechanism to be actuated rotationally to meet pre-determined course learning goals. This gave students less ambiguity and therefore fewer opportunities to explore different types of solutions. This greatly constrained students' options, making it relatively easy to get a high score in problem definition: many students simply found a mechanism that fits the requirement and put it into their documentation. In terms of the subsystem integration practice, the deadlines for the project meant that the integration and testing of the overall system were likely to happen without a deliberate decision by the student, again, making it relatively easy to get a high score

A perception survey completed by students after each offering asked how comfortable they were with seeking help from various sources. Students perceived CAs as more helpful in the intervention offering than in the control offering. This is despite the aforementioned 80% decrease in CA time commitment.

Conclusion & Discussion

The study presented here shows that redesigning an introductory mechanical engineering course based on the principles of deliberate practice and preparation for future learning cognitive theories can improve students' ability to solve design problems and document their design process. This re-design improved students' learning while decreasing the required resources to offer the course. We observed that students in the redesign intervention offerings performed significantly better in their final project compared to students in the control offering prior to redesign. This improvement was particularly pronounced in the effectiveness of the prototyping (purpose and efficiency of the prototypes) and the representation of the test results.

This paper, in association with our previous work [15], serves as a road map for curriculum developers and instructors in designing courses, activities, and group sessions that are more conducive to timely and specific feedback for all students. This study provides promising initial evidence that redesigning a course based on deliberate practice and preparation for future learning can improve students' performance in problem-solving and mechanical design. We believe the impact can be effective in creating a more inclusive model as we observed that the number of students scoring very poorly (<40) dropped dramatically in the intervention course (see figure 6).

While this study was conducted in the context of an introductory mechanical engineering course, the theoretical principles of such course redesign can be applied to more advanced courses and across other STEM domains. The main steps of the redesign can be summarized as 1) identifying & hierarchically organizing the course learning goals, 2) designing activities for these goals that are appropriate for students' level of incoming preparation for the course, 3) repeatedly providing students with timely, tailored, and specific feedback on their performance in these activities, and 4) repeatedly giving students opportunities to incorporate the provided feedback. Preparation for future learning and hands-on activities to prepare students for future lectures is one great scalable tool for achieving the third and fourth steps of this process.

Future work

We will continue this work by iteratively improving the individual activities in the course based on feedback and questions posed by students. At the end of each instructor-led lecture, students are asked to fill out an exit ticket prompting them to ask clarifying questions. We take note of these questions and add or refine elements of the instruction to improve the teaching at each offering. Additionally, the Slack workspace serves as a repository of students' questions and insightful points of confusion. At the end of each term, these inquiries are compiled and addressed for future offerings.

Beyond the perpetual incorporation of feedback and continuous improvement, we will interview students of the intervention offering to qualitatively examine their experience in the course. While we can witness significant improvements in student work, we want to make sure that the teaching is appropriate and approachable for all students. Further analysis of these interviews along with our perception survey related to levels of preparedness and prior making experience in high school will be conducted and the findings will be reported. Finally, we are developing a mechanical design assessment tool to measure students' problem-solving skills independent of their performance on the course final project.

Acknowledgements

We would like to thank HHMI for their continued support of students from underrepresented backgrounds through our science education programs.

References

[1] S. D. Sheppard, R. L. Anderson, and T. W. Kenny, "Three stanford faculty write about change & engineering education.," *Advances in Engineering Education*, 2021.

[2] E. Seymour, A.-B. Hunter, R. Harper, and D. Holland, "Talking about leaving revisited," *Talking About Leaving Revisited: Persistence, Relocation, and Loss in Undergraduate STEM Education*, 2019.

[3] L. Darling-Hammond, "New standards and old inequalities: School reform and the education of african american students," in *Black Education*, Routledge, 2006, pp. 227–254.

[4] M. Syed, M. Azmitia, and C. R. Cooper, "Identity and Academic Success among Underrepresented Ethnic Minorities: An Interdisciplinary Review and Integration: Identity and Academic Success," en, *Journal of Social Issues*, vol. 67, pp. 442–468, Sep. 2011, ISSN: 00224537. DOI: 10.1111/j.1540-4560.2011.01709.x. [Online]. Available: https://onlinelibrary.wiley.com/doi/10.1111/j.1540-4560.2011.01709.x (visited on 02/09/2022).

[5] H. Lowe and A. Cook, "Mind the gap: Are students prepared for higher education?" *Journal of further and higher education*, vol. 27, no. 1, pp. 53–76, 2003.

[6] E. W. Burkholder, G. Murillo-Gonzalez, and C. Wieman, "Importance of math prerequisites for performance in introductory physics," *Physical Review Physics Education Research*, vol. 17, no. 1, p. 010 108, 2021.

[7] M. J. Khan and C. A. Aji, "Tolerance of Ambiguity (Work in Progress)," en, in *2019 ASEE Annual Conference & Exposition Proceedings*, Tampa, Florida: ASEE Conferences, Jun. 2019, p. 33 443. DOI: 10.18260/1-2--33443. [Online]. Available: http://peer.asee.org/33443 (visited on 02/09/2022).

[8] S. Salehi, E. Burkholder, G. P. Lepage, S. Pollock, and C. Wieman, "Demographic gaps or preparation gaps?: The large impact of incoming preparation on performance of students in introductory physics," en, *Physical Review Physics Education Research*, vol. 15, p. 020 114, Jul. 2019, ISSN: 2469-9896. DOI: 10.1103/PhysRevPhysEducRes.15.020114. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevPhysEducRes.15.020114 (visited on 02/09/2022).

[9] W. F. Helsen, J. L. Starkes, and N. J. Hodges, "Team sports and the theory of deliberate practice," *Journal of Sport and Exercise psychology*, vol. 20, no. 1, pp. 12–34, 1998.

[10] K. Anders Ericsson, "Deliberate practice and acquisition of expert performance: A general overview," *Academic emergency medicine*, vol. 15, no. 11, pp. 988–994, 2008.

[11] E. Burkholder, S. Salehi, S. Sackeyfio, N. Mohamed-Hinds, and C. Wieman, "An equitable and effective approach to introductory mechanics," *arXiv preprint arXiv:2111.12504*, 2021.

[12] J. D. Bransford and D. L. Schwartz, "Chapter 3: Rethinking transfer: A simple proposal with multiple implications," *Review of research in education*, vol. 24, pp. 61–100, 1999.

[13] K. A. Ericsson, R. T. Krampe, and C. Tesch-Römer, "The role of deliberate practice in the acquisition of expert performance.," *Psychological review*, vol. 100, p. 363, 1993.

[14] S. Salehi, *Improving problem-solving through reflection*. Stanford University, 2018.

[15] F.-c. Krynen, C. Wieman, and S. Salehi, "Enhancing effectiveness and inclusivity of introductory me courses: A cognitive psychology approach," in *2022 ASEE Annual Conference & Exposition*, 2022.

[16] D. L. Schwartz, J. M. Tsang, and K. P. Blair, *The ABCs of how we learn: 26 scientifically proven approaches, how they work, and when to use them*. WW Norton & Company, 2016.