2026 ASEE ANNUAL CONFERENCE June 21–24, 2026 | Charlotte Convention Center, NC
Host Sponsor UNC Charlotte
Paper ID #52633

Designing a la carte Theory-to-Practice Learning Modules for a Mechanical Engineering Senior Design Course

Dr. Michael Cheadle, University of Wisconsin - Madison

Dr. Michael Cheadle is an Assistant Teaching Professor and Senior Design Program Coordinator at the University of Wisconsin – Madison. He is passionate about inclusive undergraduate engineering education and the development of creativity and design thinking in undergraduate students. His current focus is on the development of all aspects of senior design programs at large enrollment universities.

Dr. Katherine Fu, University of Wisconsin - Madison

Dr. Kate Fu is the Jay and Cynthia Ihlenfeld Associate Professor of Mechanical Engineering at the University of Wisconsin-Madison. From 2014 to 2021, she was an Assistant and Associate Professor of Mechanical Engineering at Georgia Institute of Technology. Prior to these appointments, she was a Postdoctoral Fellow at Massachusetts Institute of Technology and Singapore University of Technology and Design (SUTD). In May 2012, she completed her Ph.D. in Mechanical Engineering at Carnegie Mellon University. She received her M.S. in Mechanical Engineering from Carnegie Mellon in 2009, and her B.S. in Mechanical Engineering from Brown University in 2007. Her work has focused on studying the engineering design process through cognitive studies, and extending those findings to the development of methods and tools to facilitate more effective and inspired design and innovation. Dr. Fu is a recipient of the NSF CAREER Award, the ASME Design Theory and Methodology Young Investigator Award, the ASME Atlanta Section 2015 Early Career Engineer of the Year Award, and was an Achievement Rewards For College Scientists (ARCS) Foundation Scholar.

Hunter Kent, University of Wisconsin - Madison

Graduate student at UW Madison pursuing a master's degree in mechanical engineering.

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abstract

Many core classes in Mechanical Engineering, for a variety of good reasons, tend to focus on developing students' theoretical knowledge. For some of these classes, this theoretical knowledge is put into practice in laboratory courses, where students are asked to take data on well-designed, robust test apparatuses and analyze that data using theory. Trying to reconcile data with theory can be a hugely rewarding learning experience, reinforcing both theory and application. However, these laboratory courses typically don't provide students the opportunity to apply theory directly, in the context of an open-ended design problem. Instead, most institutions, including our own, ask students to do this during their senior design projects with limited support. In most cases, this support is a faculty instructor asking students, on their own, to revisit or remember previous course material and apply that knowledge to help them develop a prototype, with an implicit expectation that students will be able to do this well. However, many students struggle with this task, which can lead to poor prototyping outcomes and a general lack of confidence in their abilities. This work-in-progress paper discusses the development of a la carte, theory-to-practice learning modules designed to help students through the process of applying theory to open-ended design problems. We describe the current state of our senior design laboratory, the mechanism for gathering information from our design students who use the lab, and the initial design of a theory-to-practice learning module that will be implemented in the course in future semesters.

motivation

At UW Madison, mechanical engineering students are required to take a two-semester capstone design course centered around project-based learning, similar to that described by Dym in [1] and [2]. This course tasks teams of four students to develop a solution to a client's problem. Clients include industry sponsors, research faculty, community members, engineering design competitions, and student entrepreneurs. At the start of the course, student teams engage with their client to understand high-level requirements and translate those requirements into engineering specifications. During this time, student teams research and benchmark previous solutions and determine where these previous solutions succeed and fail in the context of their client's problem. Once the problem is defined, students generate conceptual solutions, evaluate possible solutions against the needs of their client, and then make a decision about the best path forward. For the remainder of the course, teams build prototypes, testing their designs against specifications and client requirements, adding features, exploring tradeoffs, and optimizing performance.

Throughout this design process, student teams are supported in three ways: 1) course content, 2) regular meetings with teaching assistants and faculty, and 3) prototyping resources. Course content is related to teamwork, communication, the design process, and prototyping. It is delivered via in-person lectures and on-line lessons, with a focus on direct application to their project, rather than abstract concepts. Currently, the department supports nearly 80 projects per year, engaging 8 to 10 teaching assistants, and nearly 40 faculty members. In addition to teaching assistant and faculty support, student teams have access to significant prototyping support at both the college and department levels. At the college level, student teams have access to the Grainger Engineering Design Innovation Lab [3], a 25,000 square foot facility with a variety of both maker and traditional shop equipment and tools. At the department level, student teams have access to the Mechanical Engineering Design Lab. This lab is dedicated to the senior design course and is run and maintained by teaching assistants in the design course. The focus of this lab is to support senior design teams with instruction, tools, and equipment that are not readily available in the Design Innovation Lab.

A primary challenge inherent to this course structure is providing the right support to students at the right time. Because the course engages a variety of teaching assistants and a variety of faculty, student teams, working on a variety of projects, are not always offered the support they need at the time they need it. In particular, we commonly ask student teams to revisit or remember previous course material on their own and apply that knowledge to help them develop a prototype. This application of class knowledge ranges from applying theory learned in heat transfer for designing heat exchangers, to sizing and designing bearings and gears from design of machine elements. The implicit expectation amongst most teaching assistants and faculty is that students will be able to do this well. However, many students struggle with this task, often drawing on previous solutions rather than from theory. This is consistent with work done by Cross [4][5] and differs from what is often observed in experts. This in turn often leads to poor prototyping outcomes and a general lack of student confidence in their abilities. To provide better support to our student teams, we are working to develop a suite of a la carte, theory-to-practice learning modules designed to help students through the process of applying classroom theory to open-ended design problems. We use the term “theory” to mean anything students learn in the classroom that is commonly abstracted from its application in a design context.

The concept of theory-to-practice learning modules is similar to the concept of designettes [6]. Like designettes, these theory-to-practice learning modules are self-contained and intended to be short-term experiences. However, where designettes focus on bringing design concepts into more traditional classroom spaces, theory-to-practice modules focus on bringing traditional classroom theory into longer term design projects, such as those found in two-semester, capstone design courses. Both focus on integrating fundamental aspects of engineering into design contexts.

methods

In order to identify opportunities for theory-to-practice learning modules, we are conducting surveys, gathering data from student weekly progress reports with the help of teaching assistants, and developing a camera system paired with 3D printer and laser cutter station queues that track lab use. Each of these methods, and some preliminary results, are described in more detail below.

Survey Design and Data Collection. For this work, the team used self efficacy surveys to gain insight into student behavior given their validation in both engineering education [7] studies and psychology research [8]. Survey questions were developed to set a baseline for student confidence across the different phases of design, ranging from ideation and problem definition to prototyping and technical communication. These self-efficacy surveys are distributed to all students in the senior design course using Qualtrics. When administering the initial survey, students were given a brief explanation of the surveys alongside the overall goals of the study. As stated, all students were required to fill out the surveys as a part of the course; however, in the initial briefing, students were given a consent form and asked to provide a digital signature. If students consented, they were agreeing to allow their course data to be used in publications such as this. As an incentive, students were offered 5 points of extra credit on their final report. To date, there have been two surveys administered to students with some results shown in Figures 1 and 2. Both figures are derived from the initial survey given during week 8 with 205 consenting responses. These figures show that most students are fairly confident in their ability to use sketches and create low fidelity prototypes; both of which are areas that theory-to-practice learning modules will be tested on. However, overconfidence is expected due to social desirability responding [9], as all plots are skewed in a similar manner. Data is omitted here if students did not consent, or accidentally started the survey more than once.

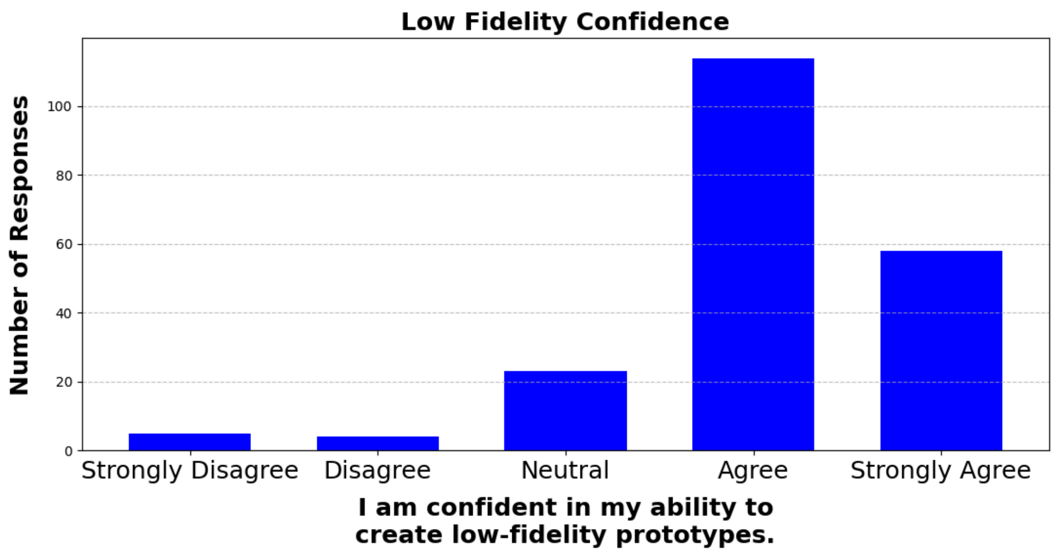

Figure 1: Self-efficacy survey question results when asked about students ability to communicate using sketching (n = 205).

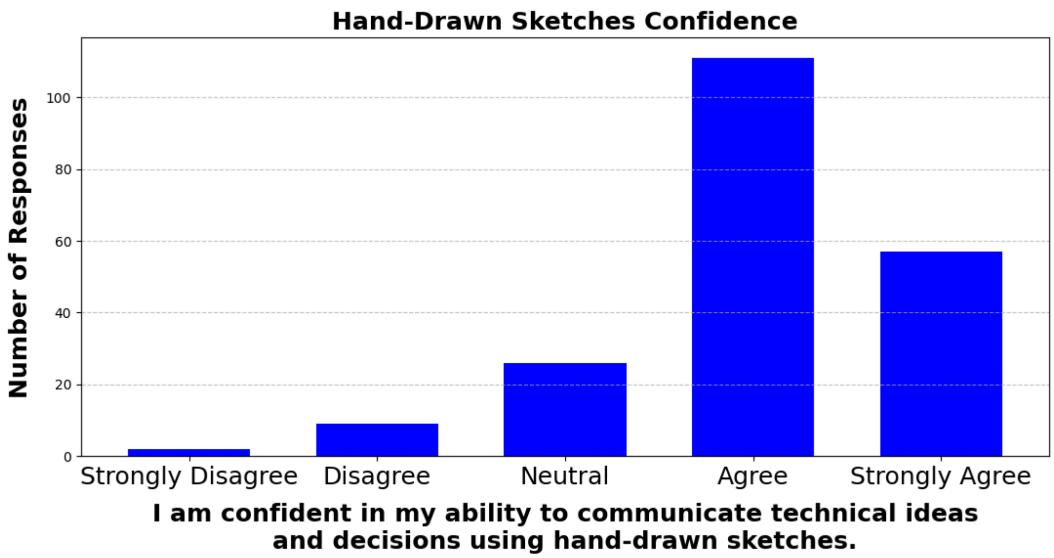

Figure 2: Self-efficacy survey question results when asked about students ability to create low fidelity prototypes (n = 205).

Going forward, students will be surveyed about their lab use every three weeks. These surveys will look to gain a better understanding of what tools and design frameworks were used. While also allowing students the ability to voice areas in which both the lab and supplemental course information is lacking. This will be accomplished by asking multi-select questions, where students indicate which tools in the design lab they used while also indicating how they spent their time in the lab, with options such as meetings, prototyping, and brainstorming, among others. Additionally, a final survey will be administered that mirrors the initial survey students took, allowing for observation on how students' self efficacy changes over the course of their two semesters. This data will be used in conjunction with observations made from course deliverables.

Data Collection from Course Deliverables. The main source of feedback on a weekly basis for students comes from their progress reports. Twenty-four hours before their faculty mentor meeting, students are required to submit a report that outlines both their plans for the coming week and what was accomplished in the prior week. Moving forward, TAs will be highlighting when student teams are observed creating low-fidelity prototypes or implementing hand-drawn sketches in their design process. These observations will be given to the research team to code the data and will be used in tandem with observations about larger team deliverables. Progress reports are often worked into larger team deliverables during weeks five, ten, and fifteen as part of their check in reports and presentations. Following some of the work done by Camburn et al. [10], prototypes will be broken into four main categories. The categories are scale (reduced or final), medium (physical or virtual), system (isolated or integrated), and requirements (relaxed or full). By recording the types of prototypes students are most often using, the research team can both look to fill knowledge gaps that may be preventing students from using certain categories of prototypes, while also looking to expand their knowledge in areas of more frequent use.

In addition to collecting data from weekly reports, course teaching assistants alongside the research team have access to laser cutting and 3D printing queues, both of which are used to record how often these machines are used. This data can be paired with TA observations in progress reports to get a better understanding of what tools and processes students are using to prototype.

Data Collection via Lab Cameras. Alongside TAs being present in the lab space, cameras have also been set up in an effort to create a time heat map that could be used to track when students are using the lab. Currently two Raspberry Pis are each linked to a wide lens Raspberry Pi cam, taking images every 5 minutes. A 2D, bird's eye view of the room layout and camera viewing angles can be seen in Figure 3 with important stations called out with text. The dashed tables are less important for capture as they are typically occupied by TAs.

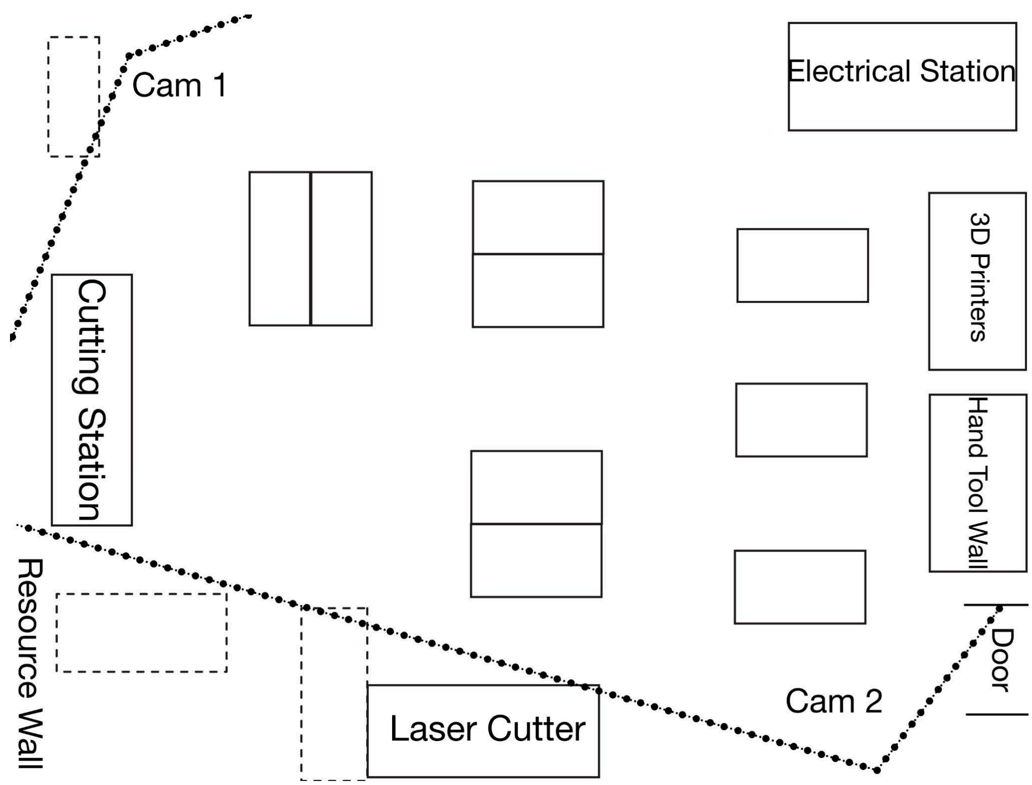

Figure 3: Bird's eye view of lab space with key tables labeled. The dashed tables are primarily used by TAs whereas the unlabeled black tables are typically used by students. The dotted lines indicate the field of view of the cameras (120 degrees).

The images are saved in a format that records the date and time of each image. The images are then processed with computer vision in MATLAB, which returns the number of people in each photo. One of the training images can be seen in Figure 4, with a more zoomed in view in Figure

5. The image was taken by cam 1 with boxes around all of the students being applied by MATLAB.

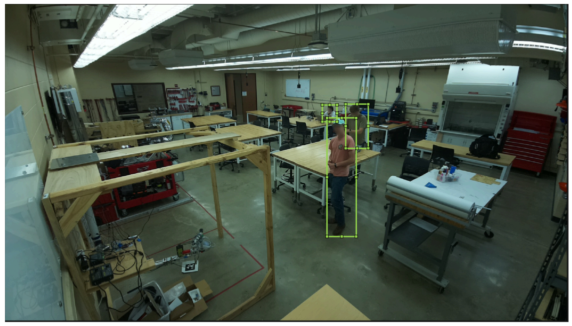

Figure 4: MATLAB Computer Vision training data with 3 students highlighted. (Picture taken from cam 1)

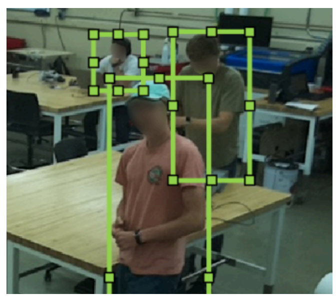

Figure 5: Enlarged view of students being tracked using MATLAB Computer Vision. (Picture taken from cam 1)

This data is used to create time maps over the course of the week, providing insight into when students are using the lab. The research team is working to expand these cameras to begin capturing how often the various stations in the lab are utilized. This will be accomplished by capturing how many students are recorded interacting with designated spaces, as labeled in Figure 3. Additional cameras may be added to help identify the different zones, helping ensure the student count in the various zones is more accurate.

potential proposed learning modules

Data collection using the three methods described above is currently underway. Though quantifiable data is not yet ready for publication, initial qualitative assessment of the survey data, progress report data, and image data indicate three possible learning modules: 1) rapid, low-fidelity prototyping, 2) sketching, and 3) motors and electronics. The motivation for each of these modules, a brief description of what they contain, and how they will be evaluated is provided below.

The notion of a prototype's fidelity was defined by Virzi [11], in the context of user interfaces, as "a measure of how authentic or realistic a prototype appears to the user when it is compared to the actual service." Fidelity, then, correlates directly with the amount of resources needed to develop a prototype. Since senior design projects in mechanical engineering almost invariably have limited resources (student time, budgets, etc.), the value of a low-fidelity prototype is significant. Ali and Lande [12] define a low-fidelity mechanical engineering prototype as a prototype that aims to test design ideas without containing all the fine details of a finalized model. That is, a prototype that requires few resources but with the potential for high impact on the development of the design. In our course, we encourage students to build such low-fidelity prototypes using basic materials (e.g., foam core, glue, cardboard, tubing, wire, etc.). This is in contrast to detailed CAD models, which, though useful, typically put a large focus on one conceptual solution [13] and require more significant resources to develop. The hope is that in many cases, a rough prototype made out of cardboard, foam, and crafting material could better answer early conceptual design questions more rapidly, with fewer resources, and help students better evaluate a wider range of conceptual solutions to client problems. Currently, student progress reports contain few examples of low-fidelity prototyping, and image data, along with TA observations in the lab, show the cutting station (shown in Figure 3) is underutilized. The intent of the module, then, is to provide students with clear examples of low-fidelity prototypes, their importance and potential impact on their design, as well as descriptions and instructions of tools and materials necessary to build them rapidly. The hope is that both students and TAs, after engaging with the learning module, will better recognize opportunities for low-fidelity prototypes and have the knowledge of the tools and materials necessary to build them.

The second module expands on what students learned in previous courses about drawing and sketching. Sketching is an integral part of design, as it allows for the communication of ideas quickly and effectively, while also helping avoid students' tendency to fixate on one idea, like what is often observed with the use of CAD [13]. This module will assist students in getting back up to speed on material that was often learned in courses taken late first year or early second year, while also giving them resources to build upon that previous knowledge. More specifically, the module would refresh students on sketching in 3D using 2-point perspective and put these sketches in the context of creating storyboards and developing conceptual solutions. Creating storyboards through sketching, as described by van der Lelie [14] in the context of product design, will help students highlight the key features and use cases of their design, allowing them to better understand their client and define their needs. Sketches will also be used to help students understand the importance of developing and evaluating conceptual solutions, a crucial step in the design process. Though we see a small amount of sketching in the progress reports collected, there still appears to be a significant opportunity for students to sketch more and to help students (and TAs) understand the importance and relevance of sketching in the context of the design process.

The final module expands on students' knowledge of motors and electronics learned in their introductory mechatronics course. The module begins with a brief review of what students learned in mechatronics and then quickly gets students up to speed on how to design and use additional motors and motor controllers that are common in senior design projects. This includes practical concerns such as mounting, reaction forces, power supply and battery selection, etc. In addition, the module will provide more advanced techniques and components for building simple breadboard and perfboard circuits and discuss best practices for soldering. Similar to data from low-fidelity prototypes, student progress reports contain few examples of motor design and use, and image data, along with TA observations in the lab, show the electronics station (shown in Figure 3) is underutilized.

Modules will be evaluated by comparing student responses to self-efficacy surveys before and after engaging with the learning modules and by collecting and evaluating student design work communicated in progress reports and milestone reports. The research team has already begun tracking student design team deliverables without access to the learning modules to serve as a baseline control condition. Modules will also be iteratively improved by collecting short form responses from students, faculty experts, and TAs.

conclusion

This study looks to explore the effects of theory-to-practice learning modules on a capstone design course. The motivation for these modules comes from the fact that students often struggle to apply classroom theory readily and productively during the design process. Part of the reason for this is a lack of directed support to students due to the distributed nature of instruction and the wide variety of projects supported prevalent in mechanical engineering. In the end, these modules should help students more readily integrate prior coursework and theory into their design process, helping students to develop solutions that better match client needs.

The first step to developing these theory-to-practice learning modules is to identify opportunities where they are most impactful. Once identified, the next step is to develop these modules for students and evaluate their efficacy. Our approach to identify opportunities is threefold: 1) the collection of student feedback via surveys, 2) the collection and evaluation of student work via weekly progress reports, and 3) the implementation of cameras in our design lab to assess usage patterns. Preliminary, qualitative data indicate three learning modules that could benefit students: rapid, low-fidelity prototyping, sketching, and motor and electronics design and use. These modules are currently under construction and will be implemented in a future semester. Their effectiveness will be evaluated by comparing student self-efficacy responses before and after engagement with the learning modules and by collecting and evaluating student design work communicated in progress reports and milestone reports. Collected self-efficacy data, along with short form feedback from students, faculty experts, and TAs will be used to iteratively improve modules as they are used.

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