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An Approach for Young Professionals to Teach Design Courses

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Abstract:

How can "young professionals" inspire and direct capstone students when we have not been "professionals"? I have been involved in running capstone design courses for mechanical engineering since Fall 2011 except for one year of sophomore design, and this has always been the most challenging issue. This paper proposes a targeted approach to teaching design courses for young academics who lack real-world design experience.

Campus Background and Course Information:

Capstone design courses are used extensively in accredited engineering programs to satisfy the Accreditation Board for Engineering and Technology (ABET) curriculum requirement of a "culminating major engineering design experience" [1]. These courses have been studied extensively for content, instructional methods, and assessments [2] [3]. These courses have been shown to facilitate the transition from an engineering student to a practicing engineer in industry [4].

At SUNY Maritime College, the mechanical engineering senior design course is a 2-semester sequence that begins every Fall. Due to the small size of this campus, there is typically only one or two instructors for this course, with each teaching roughly half of the 50-60 seniors. They self-select into teams of 4 or 5 students to work together for both semesters. The mission of the engineering program at SUNY Maritime College is to provide both a strong analytical understanding of engineering concepts connected with practical, hands-on experience of how to apply that understanding. This includes extensive applied learning experiences in industry.

This paper focuses on discussing how this course is taught. One instructor – the author – is a "young professional". This instructor began teaching the design course as a tenure-track faculty member in AY 2015-16 during their first year out of their Ph.D. program with no full-time work in industry. The other instructor for the course fits a more "traditional" mold. They had worked in industry before returning to academia, receiving their MS in 1994 and their PhD in 2004.

As will be discussed later, comparisons will not be made between the two instructors to avoid generating friction within the two colleagues. Additionally, the goal of this paper is to elevate the performance of the "young professional" to remove student perceptions of inexperience.

Introduction:

Teaching these capstone courses can be especially challenging for new faculty who have never been a practicing engineer themselves. Students are often prone to adopt the attitude of "those who can, do. Those who can't teach". To combat this, this paper discusses a reframing of the course. This approach relies heavily on emphasizing that while still analytical, the design course is not about formulas or equations. Instead, it focuses on learning how to think.

Rephrasing the course in this way serves to direct the students toward the objectives of the course and to deemphasize experience. This is reinforced through three focus areas: reverse engineering, optimization, and leaving the student's "safe zone" of experience. Utilizing this implementation, student designs have shown marked improvement and students have indicated greatly increased ratings for the instructor regarding knowledge of material and overall effectiveness.

Reverse engineering, optimization, and leaving the “safe zone” were chosen because each focus area challenges the students to apply what they’ve already learned. With reverse engineering, students have both the question and the answer. From product specifications, they have the need statements for the design, and they have an answer in terms of a design that theoretically satisfies that need statement. Instead of searching for the answer, they have to determine how the problem fits together. They have to explain through engineering principles how the design – the answer – meets the need – the question – and then perform tests to determine if it does in practice. There is no new material or theory presented here, merely an application of what they have already learned. This approach redirects students from questioning instructors whether something is done in practice to why something is done.

The next focus area, optimization, pushes the students to figure out what questions they should be asking by considering the scope of complex problems. Rather than focusing on, for example, what diameter is necessary for a shaft, students have to determine what they would consider the “best” shaft and then define what performance specifications the shaft must also meet. Again, there is no new material or theory. Often times, this is just a matter of increasing the scope of problems already done to consider the surrounding environment or initial assumptions. Once this is done, optimization tools picked up in mathematics courses can be applied to generate solutions. This has the additional benefit of forcing students to try to perform concrete analyses of their design problems instead of utilizing a guess-and-check or a duct-tape-and-super-glue approach.

Lastly, once those topics are covered and students are comfortable with the idea of applying what they have learned to familiar problems, they need to be presented with unfamiliar problems. These problems are outside the “safe zone” of their previous courses, meaning that students cannot go back and lookup solutions. This is typically the hardest step. Students are always looking for “the formula”, but a large component of design involves working where no formula exists. They need to apply what they have learned to develop the formula on their own. For example, a commonly studied and taught heat transfer problem deals with flow perpendicular to an infinitely long pipe. In practice, flow often runs parallel to finite-length pipes. If students can complete this transition toward applying what they have learned to foreign problems, they produce noticeably improved designs.

Course Focus Areas:

Reverse Engineering:

The mechanical engineering capstone design course at SUNY Maritime College begins with a reverse engineering project. The students are given a physical product – such as a cordless drill shown in Figure 1 – and tasked with performing the mechanical analyses to demonstrate that the product can meet the stated specs without failing. The reverse engineering project is chosen such that the analyses are almost exclusively relegated to their previous coursework. For the cordless drill, the motor is a brushed DC motor with a linear torque-speed curve and a linear speed-voltage relationship. Since the motor generally won’t have a detailed spec sheet, the students can perform a series of tests to determine these properties. This enables them to utilize their experience in laboratory courses to design and conduct experiments.

As this course is for mechanical engineering capstone, the products are usually selected such that they utilize a gearbox in some way. The output of the drill motor is passed through a multi-stage, planetary gearbox, allowing students to analyze the shafts, gears, and bearings through the methods they learned in a traditional machine elements course. Unlike problems in that course, however, very little information is available on the specific elements. For example, the nominal diameter of a gear is an imaginary circle between the outer diameter of the gear and the diameter at the base of the teeth. As students work to determine these dimensions, it reinforces their previous learning by forcing them to apply what they already know before attempting any calculations.

The control system for the drill is a single switch for direction and a single trigger for speed. While the controls are open-loop, the circuit board is simple enough for students to be able to trace it out. This allows them to see how the material from their circuits class is put into practice. Course topics from heat transfer and fluid mechanics courses are harder to incorporate unless the products are dedicated to that application, but students can still model and analyze the parts. For example, the drill motors include internal fans to prevent overheating. This allows an initial calculation through heat transfer on the required airflow to ensure the temperature of the drill does not exceed a critical temperature for the motor.

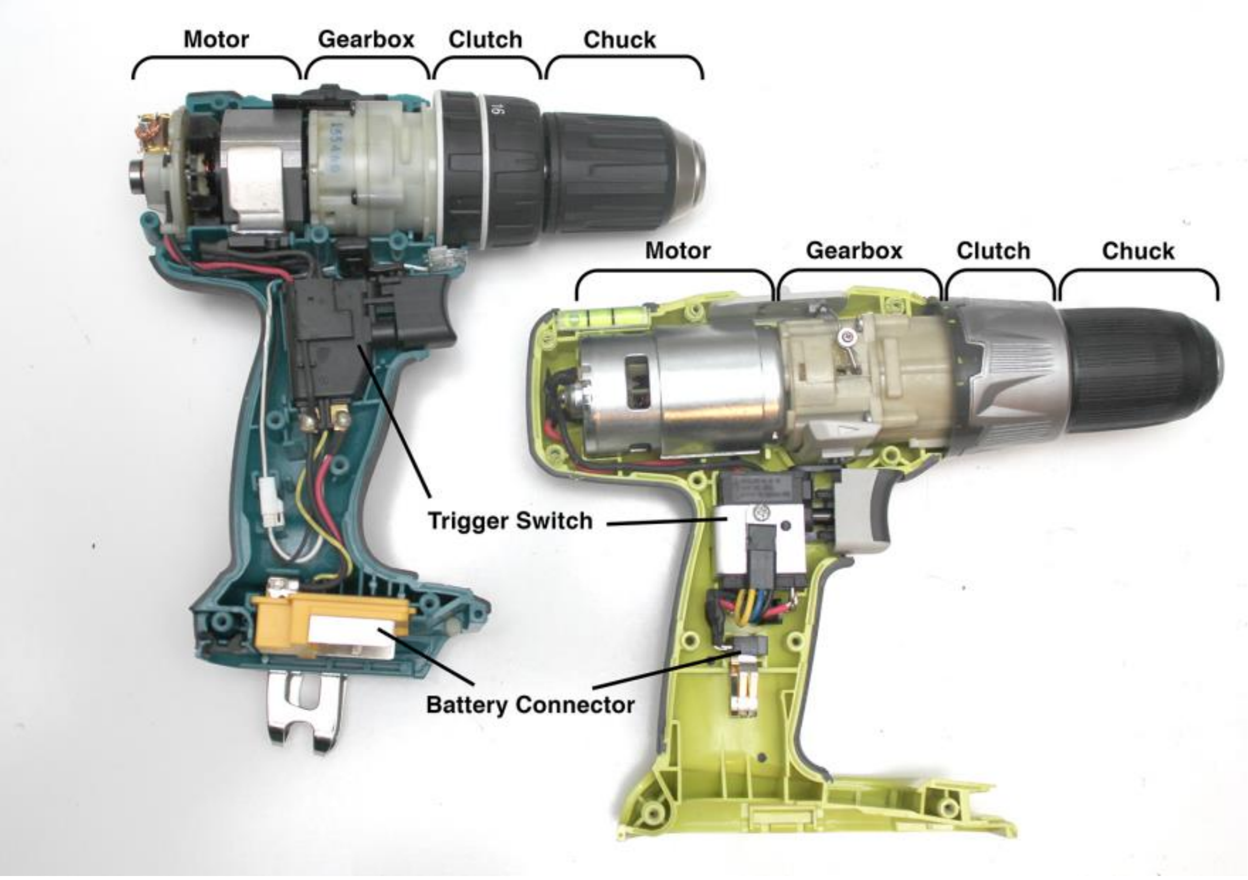


Figure 1 - Internals of Cordless Drills [5]

At the core of this project though is a reminder that there is little to no new material. Battery performance and chemistry may be a mystery to the students, but all other calculations are pulled from existing knowledge.

At the same time, the project allows opportunities to springboard into typical topics in a design course. For example, a cost analysis can be performed on the drill and manufacturing techniques can be discussed during this analysis. The students can search for manufacturing marks like ejector pin impressions and knit lines to determine how the plastic parts were injection molded.

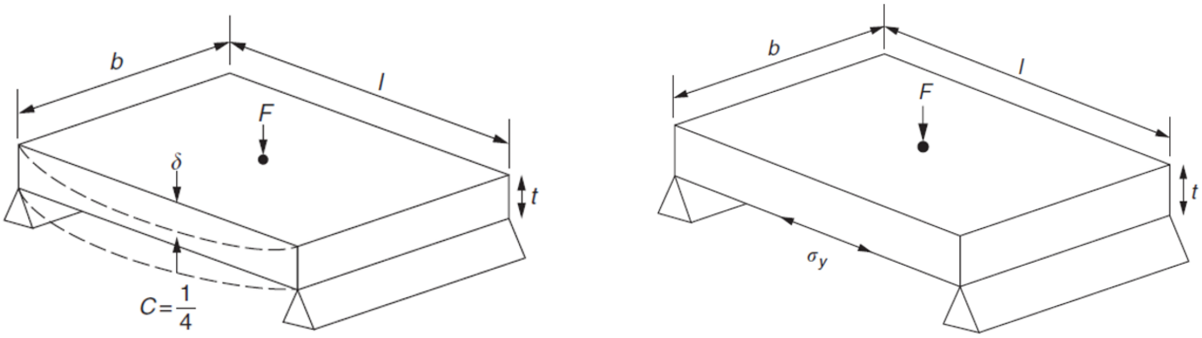
During this process, instruction is built around helping students figure out the thought processes and design choices made by the original designers. The instructors can provide insight here without relying on previous experience. For example, instead of discussing how they have designed parts or seen parts designed to reduce costs, a young professional can point to manufacturing artifacts to help students identify how a part was made and why. They can show students they have a mastery of subject matter without needing to show experience.

Optimization:

Once the topics needed for the reverse engineering project are covered, the lectures for the course transition to optimization. The optimization topics begin with material selection through Ashby charts before going on to more generic techniques like Lagrange Multipliers and Karush-Kuhn-Tucker conditions. By starting with material selection, the students are presented with a relatively simple optimization task: isolate a material index and then maximize it.

These problems utilize straightforward loading conditions like simply supported beams and panels or cylindrical members under tension and compression, but the students must begin to determine how to apply the equations they learned in their strength of materials course. Figure 2 shows an example problem. Students must combine the written equations with their existing knowledge to generate a solution. In this example, there are two failure modes – deflection and yield – and two different force terms – the applied load (F) and the load that would cause yield (F_{crit}). While students may not have learned the specific equations for a simply supported panel, the process is identical to that of a simply supported beam. The objective here is to force the students to determine how to think about how to apply the equations they've learned previously.

Problem 1: The loads on automotive door panels are modeled by a simply supported panel as shown below. Using the equations provided, determine the lightest material if the deflection cannot be more than (δ_{max}) and the material cannot yield.



$$\delta = \frac{C * l^3 * F}{E * b * t^3}$$

$$F_{crit} = \frac{\frac{2}{3} * b * t^2}{l} * \sigma_y$$

Figure 2 - Example Material Selection Problem

Utilizing the Ashby chart approach allows the students to bypass much of the complex mathematics involved optimization. Students solve the problems by creating a function such that the parameter to be maximized or minimized is a function of a constant multiplied by a material index. These functions are generated primarily through substitution. In the example above, the yield condition gives a result of $m = K * (\frac{\rho}{\sigma_y^{0.5}})$, where K is a constant, by substituting for the unspecified thickness. The optimal value then is just the materials with the lowest ratio of density to square yield strength, which can be found on the Ashby chart for yield strength vs density.

Using this experience as a basis, students can then proceed to the more advanced optimization methods with a foundation on how to approach a problem. They can identify constraints, generate appropriate performance metrics, and apply their previous knowledge.

While optimization is a critical, inherent skill in engineering design [6] [7], the goal here is not just to teach them numeric or analytical optimization. Instead, the goal is to give them practice in applying their existing knowledge to properly formulate the complex systems of equations. This translates directly into their forward design process as they must balance the tradeoffs that inevitably arise.

For a young professional, this often leans into their strengths. Most of these faculty members have recent experience in theoretical calculations through graduate school. They can demonstrate experience and understanding of the course material.

Leaving the "Safe Zone":

The conclusion of the optimization lectures is timed to coincide with the conclusion of the reverse engineering project in Week 7 – the midpoint of the first semester in the sequence. This means that students are now equipped with the tools to succeed in forward engineering design. Students are then given a design project for the remainder of the year. The instructor selects these projects, and the same project is assigned to all students in the course. There are advantages and disadvantages with this setup, but the key portion is that the tasks often challenge students to work on something completely foreign to them. For example, when the reverse engineering project was a cordless drill, the final project was to create a small vessel that could clean up the local waterways near campus.

The students did not have significant experience with naval architecture, but they could identify that the thrust from the propellers must balance the drag force from the fluid. After finding the equations for thrust and drag, they can combine them into a single constraint equation for their design. Students could increase runtime by using larger battery packs, but this required additional displacement of the hull, leading to increased drag. This meant there were diminishing returns for larger battery packs. All of this needed to be completed within a specified budget between $200 and $300. While most students do not combine all of the equations into a single optimization problem, they can begin to combine some of the constraints while making certain decisions. For example, the thrust must balance the drag and the speed must be greater than some minimum, but the battery will be predetermined to have a capacity of 7.5 Ah.

There are usually incredible growing pains during this phase. Some have “analysis paralysis” while others go to the opposite extreme and default to a high school mentality of combining existing parts until a satisfactory design is achieved – a process colloquially referred to as “fabricobbling”. However, these students can usually be redirected by reminding them to apply the processes learned in class just like they applied their previous course knowledge.

Here, the conversation for a young professional is challenging, but navigable. They may not have the experience to lean on for times where they had to work in an unfamiliar environment to meet customer needs. However, by referring students back to their existing knowledge, they are underscoring that while experience is beneficial, it is not necessary to perform quality engineering work.

Discussion of Effectiveness:

As this instructional style has been applied in the senior design courses, it has demonstrated success. Students have performed better and the course evaluations for the instructor have improved. This system has been slowly developed over the course of several years and exact data was not collected on performance over the entirety of this development.

At the beginning of teaching the courses, starting in AY 2015-2016, there were typically 25% of students who met the design specifications, 50% of students who approached the design specifications, and 25% of students who were not close to the design requirements during those initial semesters. Originally, projects had to be kept small, such as an automatic espresso maker, because students struggled to meet these requirements.

Since re-framing the course to implement these changes, performance has improved. In the last pre-covid academic year, AY 2018-19, out of 12 groups tasked with developing the cleanup vessel, 2 exceeded the design specifications, 8 met the design specifications, and only 2 approached the design specifications. No groups were not close to the required minimums. An example of a student-created vessel is shown in Figure 3. The vessel exceeded expectations by incorporating ultrasonic sensors to perform basic obstacle avoidance autonomously. This improvement was not mirrored in the performance of groups with another instructors during a given semester.

Figure 3 - Example student design vessel

In addition to increased performance in the projects, the students' perception of the instructor showed noticeable improvement. Course evaluations were analyzed for a single instructor – the author – from Fall of 2018 to Spring of 2022 to track the evaluations for this instructor over time. Quantitative comparisons were not made between instructors for the course to avoid potential friction between colleagues.

Students are surveyed at the end of every semester on the quality of the course and the instructor. These results must always be used carefully. Many studies have discussed ways the data can be skewed from eliciting bias against professors of color, non-native English speakers, women, and gender non-conforming individuals [8] [9] to potentially modifying the results through feeding students cookies [10]. For this paper, all evaluations were performed in an identical manner for a single instructor. Thus, the limitations of course evaluations can be mitigated. An additional issue for this paper is that the course surveys were changed at the local level and data before 2018 is unavailable so a clear pre- and post-intervention analysis cannot be performed. However, utilizing these methods has shown continuous improvement in questions related to the instructor. Figure 4 shows the results from four survey questions since 2018. The questions are explained in Table 1.

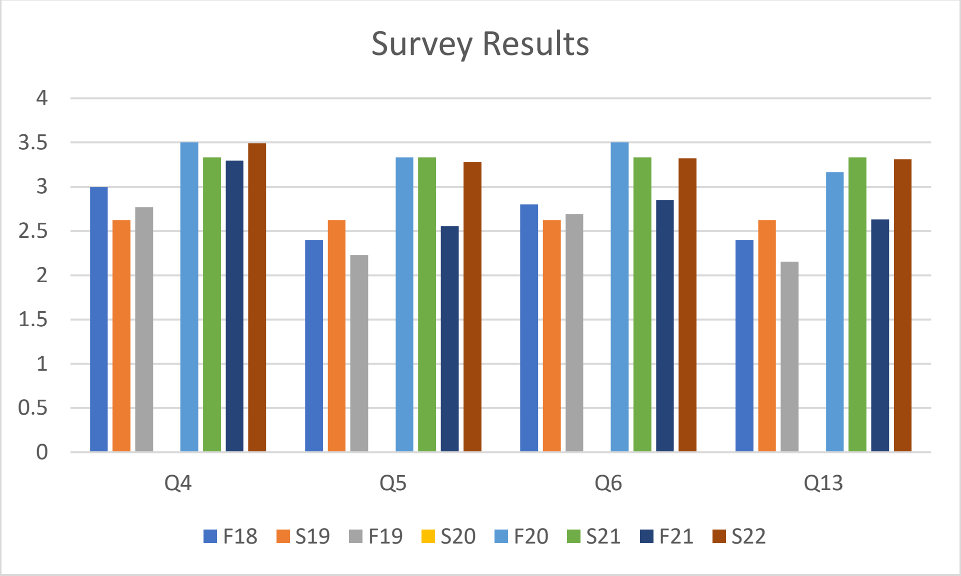


Figure 4 - Course Evaluation Results (note: data from Spring 2020 is not included due to low response rates from COVID-19)

Table 1 - Survey Question Key

Q4	The Instructor for this course - Demonstrated thorough knowledge of the subject
Q5	The Instructor for this course - Clearly explained complex or abstract ideas
Q6	The Instructor for this course - Stimulated my thinking
Q13	The Instructor for this course - Is an effective instructor

Regarding the data, results from Spring 2020 are not included due to low response rates likely attributable to shutdowns relating to COVID-19. Data for the following semester – Fall 2020 – shows a large increase, but the reasons are not clear. Course content remained relatively unchanged and instructional methods were consistent. Data across the department shows an increase in course evaluations of approximately 5% that semester. It is likely reflective of a return to “normal” for students and an appreciation of accommodations from instructors on campus. However, that is considered beyond the scope of this paper.

Assuming the data for Fall 2020 is artificially inflated slightly, the performance data steadily increases for Question 4 (Demonstrated thorough knowledge of the subject). The results end up just below the departmental average and show a 21% increase from AY 2018-19 to AY 2021-22. These are significant findings since the knowledge of the subject matter is design work despite the instructor never working outside academia and the departmental comparison includes instructors who have taught at the institution for up to 60 years.

The other questions also demonstrate an increase in performance with Question 13 (Is an effective instructor) showing an especially high 35% increase in the raw score. To normalize this relative to the department, students rated this performance 22.5% below the departmental average in AY 2018-19, but this rose to 5.8% above the departmental average by AY 2021-22.

Conclusion:

This paper suggests a strategy through which young professionals without industrial experience can provide students with the tools to succeed in their design projects. This process also allows students to look beyond the inexperience of the instructors and focus on the techniques involved in design.

Due to the variability of design projects and the small size of the institution, it is extremely difficult to compare projects. However, anecdotal performance indicators show that students who are challenged with these topics and work to overcome them produce more viable designs than those who are not. Additionally, implementing these topics as focus areas noticeably improved student evaluations of the instructor, even in areas such as subject knowledge. This means students do not see the instructor's lack of experience working in the field as an impediment.

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