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Assembly Activities for Enhancing Design Functionality

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1 Introduction

This work describes an effort to improve mechanical design education at the University of Illinois Urbana-Champaign. To achieve this goal, a new "Assembly Lab" was added to the first week of "Mechanical Design 1", a 300-level mechanical design class that has between 150 and 250 students each semester. In the assembly lab, students gain proficiency in mechanism design by exploring hands-on examples of good and bad design choices. As a result, the students are better prepared for their semester design projects. This study was classified as non-human subjects research by the University of Illinois Urbana-Champaign Institutional Review Board (#IRB25-1026)

1.1 Motivation

After analyzing student performance across several semesters of course projects in Mechanical Design 1, course staff noticed that students consistently struggled to synthesize and apply information from previous courses. Students' knowledge should carry over from previous courses; however, concepts are often lost without practice. Even when students are able to retain the information previously presented to them, they often make optimistic assumptions about the manufacturing of physical prototypes, and fail to consider the practical consequences of their design choices. This presents a gap between the skills used in the classroom and those utilized in industry or research labs. This gap has been considered by other universities, and classes have been restructured to work around the demands of industry and research labs for new graduates [1], [2], [3].

For many students, Mechanical Design 1 is the first time they are required to design, manufacture, and build a mechanical system from scratch. As a result, students are often overwhelmed with the large number of decisions and steep learning curve of the projects. To mitigate these challenges, we designed five assembly tasks to expose students to good design practices and highlight common design challenges they may have to overcome during the fabrication of their projects. These tasks were combined together into an "Assembly Lab" where the students would learn to identify good and bad design choices. Special attention was given to address challenges that were commonly observed in previous semesters. Previous research has shown that kinesthetic learning is an effective method for education. This can be observed in educational theories such as Kolb's experiential learning model where concrete experiences are critical for learning and retaining information [4], [5]. Other classes at various universities across many disciplines have embraced the philosophy of experiential learning through projects and 3D printed physical models, and they are often effective [6], [7] , [8], [9], [10].

1.2 Background

Mechanical Design 1 is the third course out of five in the mechanical design sequence in the Mechanical Science and Engineering department at the University of Illinois Urbana-Champaign. Before taking this course, students should have the prerequisite knowledge from previous courses. This includes mass manufacturing methods like injection molding, casting, and sheet metal design. Topics like fits and limits and Geometric Dimensioning and Tolerancing are covered, as are 3D printing and laser cutting. Students have also taken courses in CAD, and introductory mechanics.

This new assembly lab replaced the course's original first week lab activity. Both activities have a similar structure where students work in groups of 4 on a task and are asked to observe the operation of a mechanical system and then complete a post-lab reflection. In the original activity, students partially disassembled various elements of bicycles. Discussions with course staff indicated that this might be overwhelming to a student who has not had to think about the function of complex mechanical assemblies. Another disadvantage of this activity was that the bikes were constructed using high-quality fabrication techniques that are not available for the students to use on their class projects. As a result, students fail to learn how to construct mechanisms with the tools available in on-campus maker spaces.

1.3 Class Projects

A key aspect of Mechanical Design 1 are the two projects that the students complete over the course of the semester. These projects are one of the primary ways that student learning is evaluated. The first project is usually intended to be an introduction to mechanism design, and has simpler design requirements. In this project, students must create a mechanism that utilizes a linkage and is operated by a hand crank. The first project during the semester these activities were piloted (Fall 2025) was a dispensing mechanism. Students had to dispense five objects that had a mass of less than 25 grams with a delay in between dispenses.

In the second project, students are evaluated on their ability to perform a task with a continuous reciprocating linkage. Additional analysis is necessary with position, velocity, acceleration (PVA) analysis to determine the speed and path of the linkage. Students are provided with a motor with a 1:34 planetary gearbox (Pololu #3204), a 9.6V battery pack, and a switch. Historically, final projects have been varied and include projects such as fruit slicers, hill climbers, and rope walkers. The final project during the semester this lab activity was piloted was a walking dispenser, which students had to integrate with their first project to create a walker that will move forward and dispense objects exactly 2m apart.

2 Objectives

The purpose of this new lab is to help students understand the impact of their design choices so that they are more likely to succeed on their design projects. To provide students with realistic design consequences, we ensured that all of the assembly tasks in the lab activity were constructed using the same fabrication techniques and hardware available to them for their course projects. By exposing students to potential issues that may arise during the fabrication of their project, they will be more prepared to confidently handle them. Some of the specific shortcomings that are commonly observed in Mechanical Design 1 projects that these assembly tasks are attempting to address are discussed in this section.

2.1 Tolerances

The two primary manufacturing processes that students have access to on campus are FDM 3D printing and laser cutting. Each of the manufacturing processes has imprecision that students must learn and adapt to when designing and manufacturing their projects.

During laser cutting, the kerf of the 70 W laser enlarges holes by about 0.2 mm (approximately 0.0079") [11]. Students must learn that even a "small" deviation from the nominal size could cause slop in joints or be impossible to assemble. Additionally, the laser cutter creates a small (about 1-2°) draft angle during the manufacturing process, as the laser loses power as it passes through the part [11]. This means the holes are actually conical and edges are not perfectly square. To convey this concept to students, a hands-on approach will be used to demonstrate how the results of laser cutting are relatively imprecise.

During the process of FDM 3D printing, plastic shrinks as it cools. This, combined with the general machine tolerance, creates dimensional inaccuracy in holes that must be accounted for [12]. Additionally, holes printed vertically will be slightly flat on the top and bottom due to the nature of the process. Many options exist to mitigate these manufacturing inaccuracies such as post-processing with a drill, adjusting the slicer settings, or simply adjusting the nominal size in CAD. However, students often neglect this practical aspect of manufacturing their design, so this lab activity will show students the imperfections of additive manufacturing.

2.2 Design for Manufacturing

Often, students must design and assemble a box-like structure for their final project by joining two plates manufactured on the laser cutter together. The result is often messy and flimsy, held together with adhesives. Alternatively, students might opt to create a large 3D printed box-like structure, which is more expensive and takes significantly longer to manufacture, that could easily be made out of laser cut plates. Learning to optimize between the two primary manufacturing methods is tough to learn without practice, so the different assembly tasks are designed to highlight some of the primary uses for each.

2.3 Robustness

Students' projects theoretically only have to work once for the final performance, which leads to students taking shortcuts that make their projects fragile. One example is designing for torque transmission. For the final project, a non-trivial amount of torque need to be delivered from a motor to a linkage. To accomplish this, shafts with a D-profile (a round shaft with a flat surface) are often used, as the flat surface can transmit torque. Other times, round shafts are used, which only rely on friction to transmit torque. Both of these have significant flaws to them, which the assembly tasks intend to steer students away from. By exposing students to robust design principles, the expectation is that the students' final performances will improve.

2.4 Constraints

Degrees of freedom (DoF) in planar mechanisms and structures can be defined according to Grubler's Equation: $DoF = 3(N-1) - 2J_1 - J_2$ where N is the number of bodies/links, J_1 is the number of joints that remove 2 DoFs (pin in hole) and J_2 is the number of joints that remove 1 DoF (pin in slot). When constructing mechanisms, it is important that students understand that an underconstrained mechanism will be floppy or demonstrate otherwise undesirable behavior. If mechanisms are overconstrained, elements may need to be bent into place for assembly, creating friction and making operation difficult. This concept is taught in the lecture section of the class, but is also emphasized in this lab activity with a physical demonstration.

3 Lab Activity Description

In Mechanical Design 1, students participate in 80-minute weekly lab sessions where they collaborate with others in groups of four. This lab activity was the first lab session of the semester. After short introductions, students rotate between five assembly tasks. The lab activity facilitates rotation through a structured seating arrangement. The seating arrangement allows students to meet all 20 students in their lab section over the course of all the assembly tasks. This allows students to get to know one another and identify who they might want to work with for their project groups.

Each of the assembly tasks described in this section emphasizes at least one shortcoming that the lab activity is attempting to expose students to. These shortcomings are also further emphasized in the post-lab reflection that students must complete.

3.1 Gear Train

In their projects, students often need to implement a gear reduction to meet the torque and speed requirements of the final performance. Students often use a gear generator CAD tool [13] to create the complex gear tooth profile but still struggle with using the tool and implementing gears properly. Sometimes, the teeth are too small for proper torque transmission, leading to slip, manufacturing mishaps, or tooth failure, as observed in Fig. 1(b). Large teeth can endure higher loads, are easy to manufacture, and are robust to variability in center-to-center distance, as observed in Fig. 1(a). Other times, gears are cantilevered, which can create variability in the center-to-center distance between the gears, leading to inconsistent meshing. Often, the gears do not have a feature that engages with the shaft, such as a set screw or clamp, so the gear-shaft interface will strip, rendering the project inoperable.

This assembly task highlights these shortcomings in the bad example with small teeth, cantilevered shafts, and a shaft-gear interface with no set screw. The gears and base are 3D printed, with bronze sleeve bearings supporting the shafts. The good example has an identical base, but some subtle changes make the design more robust. The gear has much larger teeth, has a set screw interface, and is laser cut out of Acetal instead of 3D printed for tighter tolerance and lower friction.

Additionally, there is a laser cut acrylic supporting plate that can be attached to the base which makes the shaft simply supported rather than cantilevered. The plate is assembled with just one screw and two dowel pins. This feature aims to highlight the usefulness of dowel pins for precise alignment and the ease of assembly with just one screw. Lastly, spacers are included with the good example to highlight the importance of axial retention.

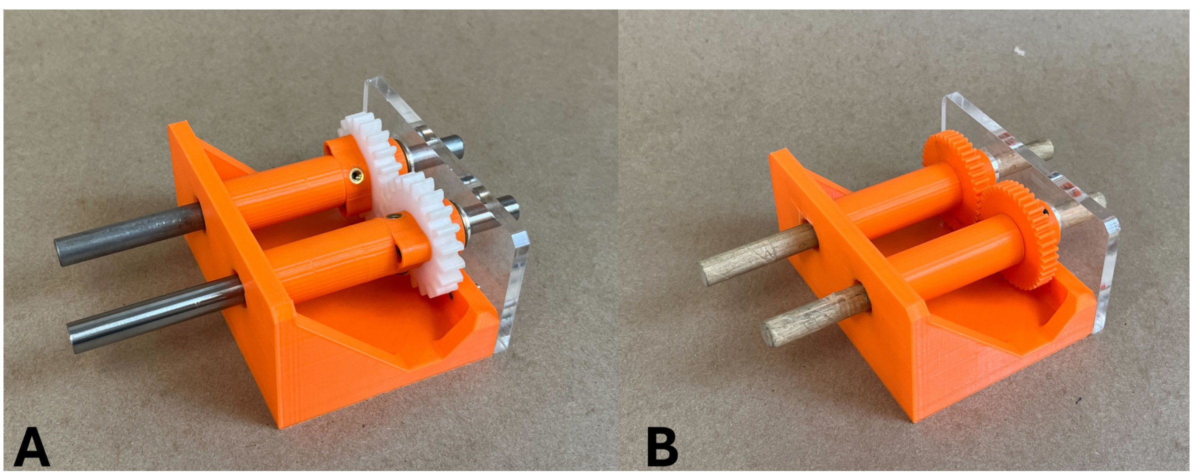

Figure 1: Gear assembly task with well designed gears (A) and poorly designed gears (B)

3.2 Cam-Follower

In the course, students learn about cam-follower mechanisms and create displacement, velocity, acceleration, and jerk profiles with trigonometric or polynomial functions. This assembly task serves to introduce students to building cam-follower mechanisms that do not bind. Thin sheets that radially retain followers are not enough to prevent followers from jamming, so axial support is needed. Even if the support is relatively loose, as long as it is long enough to prevent the follower from tilting enough to jam, the mechanism will robustly function. In Fig. 2, the left follower is constrained well and the right follower is constrained poorly. This assembly task is constructed out of 1/4" acrylic, a 3/8" D-shaft, heat-set inserts, and 3D-printed parts. The acrylic is joined together using brackets and tab-and-slot alignment features. Both the "good" and the "bad" examples have the same shaft and cam profile, allowing students to easily observe the difference between the two methods. Additionally, students learn about assembly techniques with shafts, as each cam has a set screw for torque transmission and axial retention. The assembly task also is equipped with bronze sleeve bearings which facilitate shaft rotation.

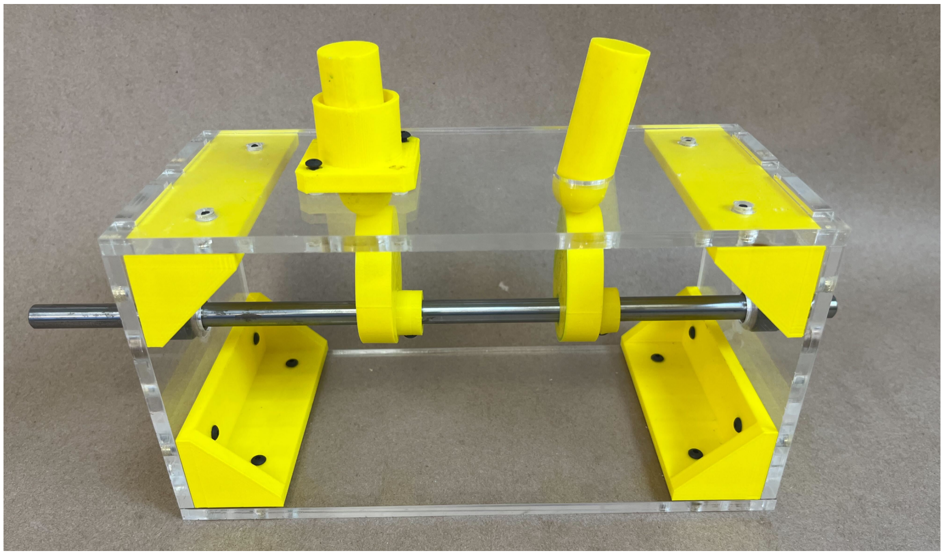

Figure 2: Cam-follower assembly task that is constrained properly (left) and improperly (right)

3.3 Crank-Slider Linkage

This type of linkage has historically been difficult for students to create without a lot of friction. This is often due to poor constraint of the slider. In the bad example in Fig. 3(b), the slider is a bolt that slides along a slot in a laser cut plate, only constraining it in one degree of freedom. This lets the slider component rotate and bind against the slot, showcasing the pitfalls of a poorly constructed crank-slider mechanism.

However, it is very simple to build a good crank-slider mechanism. In the good example in Fig. 3(a), acetal for the slider component is used for its low-friction properties. The slider also is fully constrained in two degrees of freedom by the 3D printed enclosure. This leads to a very smooth operation which students could replicate on their projects.

3.4 4-bar Linkage

The 4-bar linkage is a core mechanism studied in the course, but students struggle to build a robust linkage. This assembly task aims to teach students about the importance of proper tolerances and component selection for pin joints. Students often struggle with slop in the joints due to poor tolerances. In the bad example in Fig. 4(b), screws used as pin joints are poor due to the rough surface and unthreading themselves. Additionally, no thought is given to the axial spacing of the linkage, causing the links to interfere during rotation.

The good example in Fig. 4(a) utilizes binding barrels and screws, as that is cheap and readily available to students in the student makerspace. The smooth surface facilitates rotation much better than screws. However, even with binding barrels, slop is still present in the joints as the barrels are not properly snug in the hole. This is where tolerances are important, and how different manufacturing methods might affect the end result. For example, using a drill press may yield greater accuracy than the laser cutter due to the draft angle.

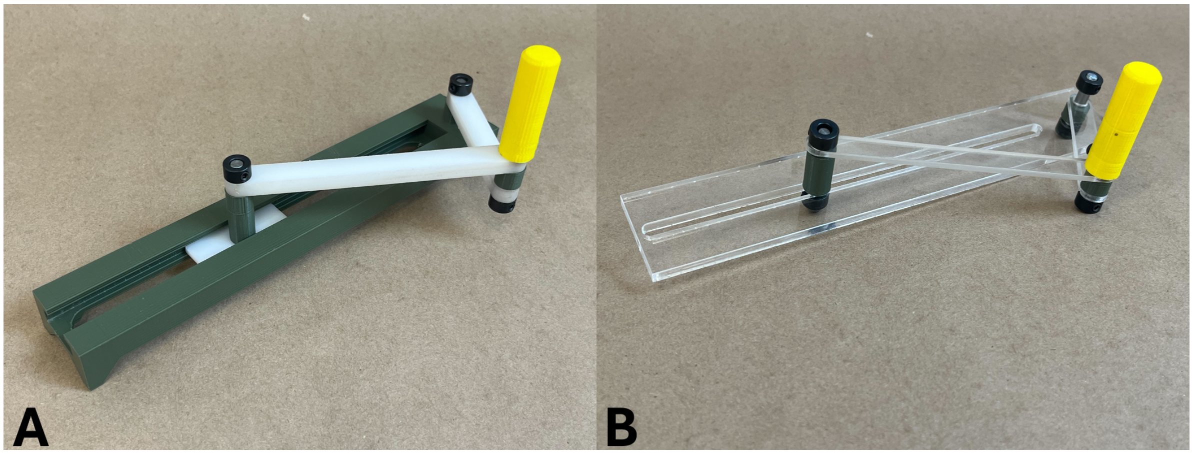

Figure 3: Crank-slider assembly task with well designed slider (A) and poorly designed slider (B)

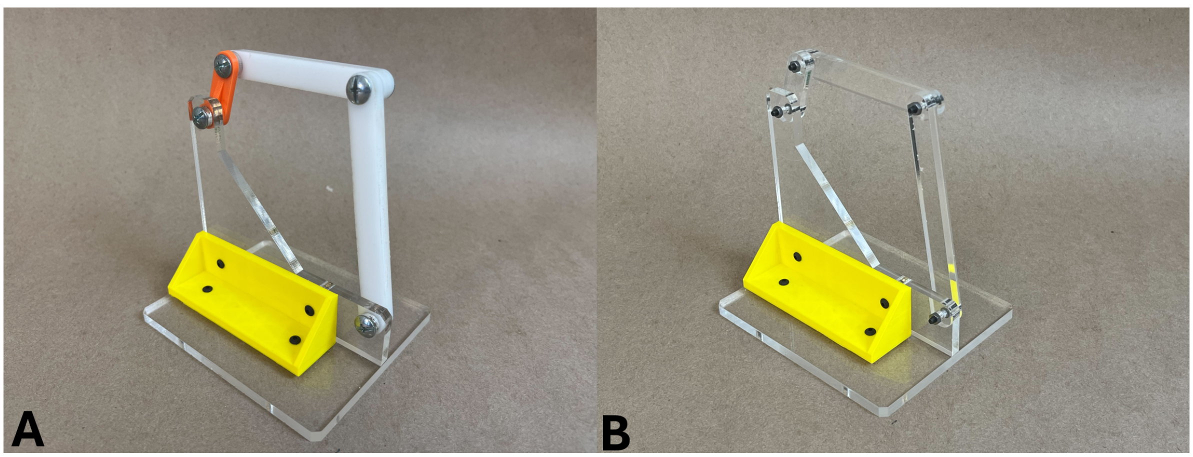

Figure 4: Linkage assembly task with well designed linkage (A) and poorly designed linkage (B)

3.5 Box Construction

Building a box could be considered rather trivial, but it is an important skill that is easily overlooked. Students often join together laser cut plates for their final project, but the methods for doing so have historically come from experience. Beginner designers will not think about this at all, while novice designers may consider glue as a primary method of joinery. This assembly task aims to expose students to more robust methods of box construction to enable them to build sturdier mechanisms, as observed in Fig. 5(a).

One of the most critical components for box construction are the brackets, and the box has a 3D printed corner bracket and an off the shelf metal bracket. The 3D printed corner bracket utilizes heat-set inserts in the side flanges to showcase the benefits of stronger threads in plastic. The bottom flange of the corner bracket has a counterbored hole to demonstrate a method of eliminating interferences with screw heads. Another method to join two perpendicular plates is the captive nut [14]. This method has a nut that rests in a slot in a laser cut component to prevent it from spinning, and allows for a compact, efficient design. The tolerances that were used for fitting the nut and the heat-set inserts are engraved into the bottom of the box. All the threads in the acrylic sheets have heat-set inserts in them to demonstrate that since acrylic is a thermoplastic, heat-set inserts can be used in them.

An additional lesson to be learned from this box is the topic of overconstrained mechanisms, as observed in Fig. 5(b). If a link is attached to a fixed plate with two screws (pin joints), it technically has -1 degrees of freedom according to Grubler's Equation. If holes have poor tolerances, such as if they are hand drilled or otherwise modified, then the link may not be able to properly be fastened to the fixed plate. This assembly task seeks to highlight the importance of pin-pin vs pin-slot hole patterns and the additional flexibility that a pin-slot hole pattern offers. This line of thinking extends beyond manufacturing tolerance: if these pieces were made of different materials and were thermally expanding at different rates, it might be important that the hole pattern does not over constrain the pieces.

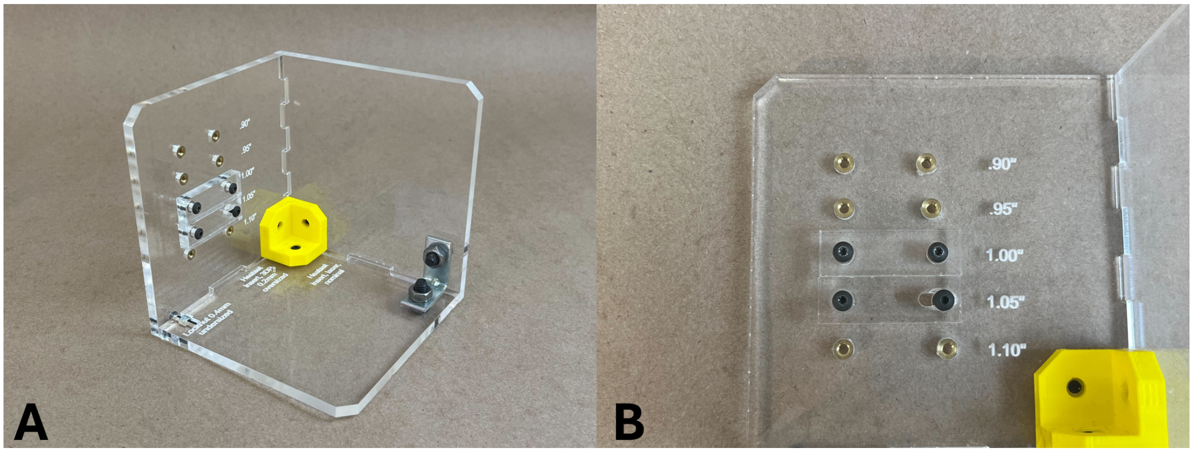

Figure 5: Box assembly task highlighting joinery (A) and overconstrained mechanisms (B)

4 Results and Feedback

To measure the efficacy of this new lab activity, we utilized both direct and indirect measurements. Surveys were administered at the midpoint and end of the semester to measure students' perceptions of the utility of the activity. We also compared Project 1 grades between different semesters as a more direct measure of the impact of the new lab activity on student project performance.

The first survey was administered in Week 8 of the 16-week semester. This was two weeks after the final deliverables for Project 1 (hand crank operated mechanism) were completed. The survey was administered in-class and consisted of a series of Likert-style questions that asked students to rate how useful different resources were for ensuring Project 1 functioned properly. Each question of the survey had between 127 and 137 responses. The raw data and exact questions are located in the appendix. A summary of the data is shown in Fig. 6.

This data indicates that while a majority of students felt that the assembly lab activity (Lab 1) was useful for them when designing the dispenser (20% strongly agree, 33% agree), there was still a significant fraction that was neutral (28%) or disagreed that the lab was helpful (17% disagree, 2% strongly disagree). Other questions in this survey asked about the impact of direct instructor feedback that was provided via in lab design reviews, and students' own research. Students felt that these activities were even more helpful, indicating that from the perspective of the student the lab activity alone may not be sufficient to ensure the success.

We also note that this survey was administered seven weeks after the assembly lab activity (Lab 1), whereas design reviews had occurred only two and four weeks before the survey, meaning that there is a potential for recency bias to impact the results.

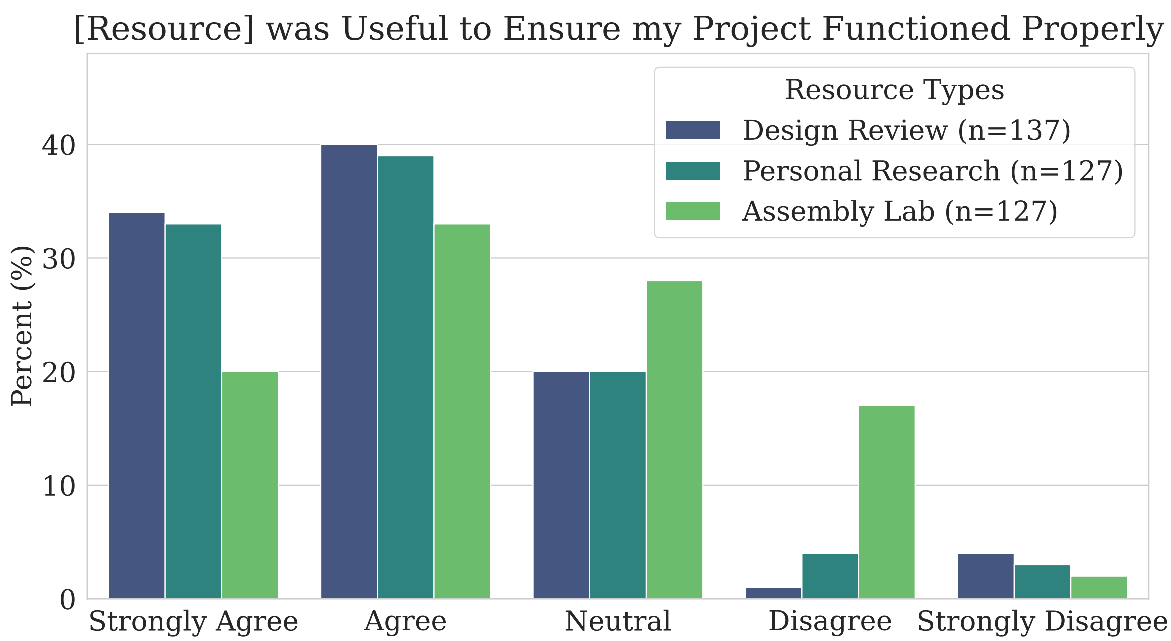

Figure 6: Plot of Mid-Semester Survey Data

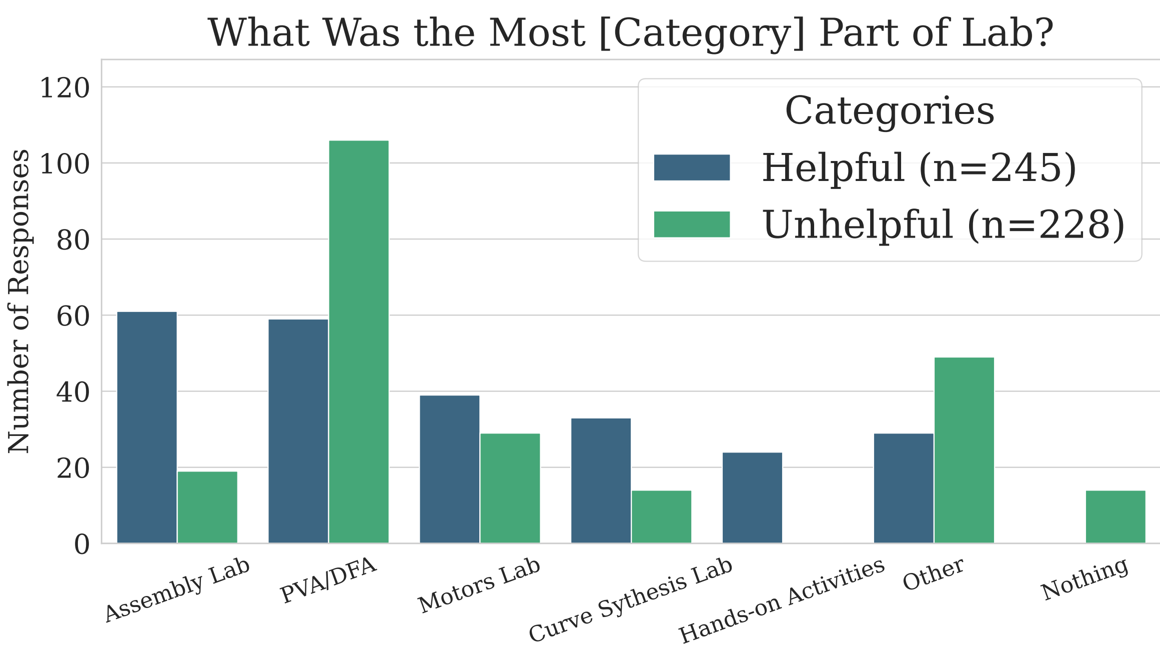

Figure 7: Plot of End of Semester Survey Data

Another take home survey was given to the students at the end of the semester, asking students to rate what the most and least helpful things that they learned about in lab. Students provided short written answers, which were then coded by a third party. The responses were not tied to a single lab, and some responses were more general or related to several topics. The raw data can be located in the appendix. A summary of the data is shown in Fig. 7.

This data indicates that the assembly lab presented in this work is the most commonly listed helpful item from the lab section of the course with 61 responses. We note "hands-on activities" could also include the assembly lab activity, but could also include labs focused on motor characterization or curve synthesis. Additionally, relatively few students (16) felt that this lab was unhelpful. This suggests that at the end of the semester students felt that the assembly lab was the most helpful activity that they completed this semester. Other lab activities had far fewer students select them as helpful, and the other activities had a more equal ratio of "helpful" to "unhelpful" responses.

The data in Fig. 6 demonstrates that students felt that activities other than the assembly lab had a greater impact on their success on the easier task in Project 1. However, the data in Fig. 7 shows that the value of the assembly tasks became more clear to students later in the semester as they worked on the more complex Project 2.

As a direct measure of the benefit of this new lab activity we compared grade distributions of the "functionality" grade for Project 1 between several semesters. This rubric item was associated with the operation of student designs. Designs that could be operated with minimal force, while completing a given task were categorized as "Mastered". Designs which occasionally failed or were difficult to operate were given "Proficient" scores. Designs that were unable to attempt the given tasks or required substantial intervention to function were graded as "Developing". We note that this is not a perfect comparison, as in Project 1 the task was more complex than in previous semesters.

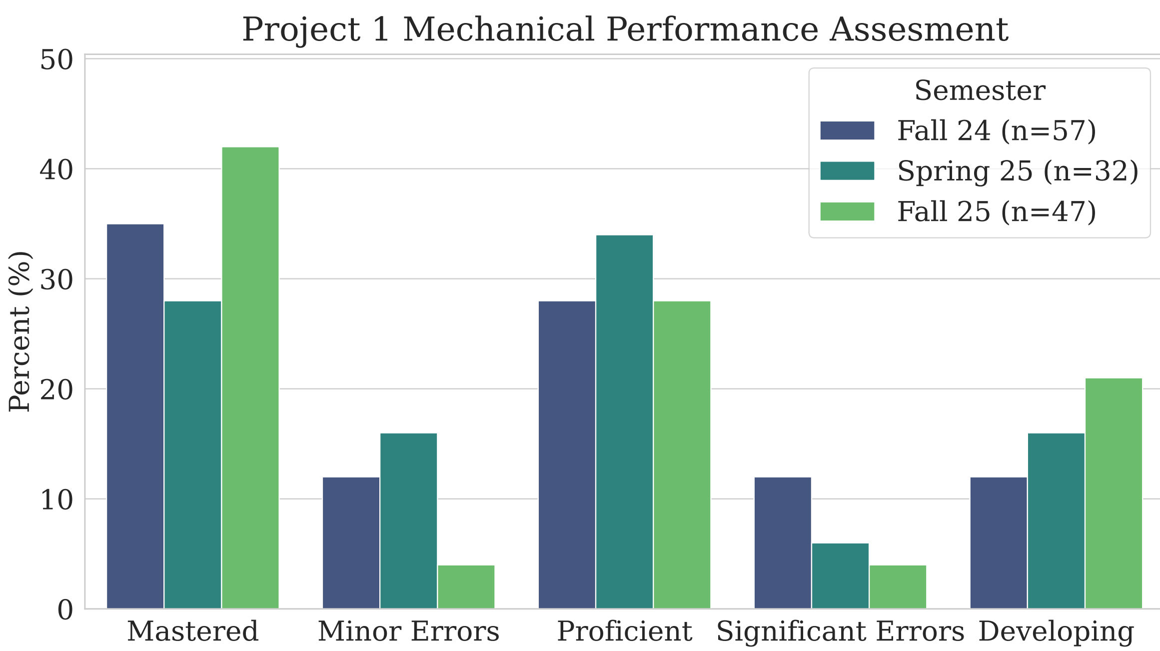

Figure 8: Plot of Project 1 Mechanical Assessment Data

In the Fall of 2024 and Spring of 2025, students' Project 1 was to create an automaton that could operate smoothly. In contrast, during the Fall 2025 semester, students needed to design a dispenser, and students lost points if it did not dispense five objects in a regular controlled manner. This increase in difficulty would have traditionally decreased the average performance. However, the average scores were about the same (2.45 in Fall 24, 2.34 in Spring 25, and 2.42 in Fall 25) and a larger proportion of students got full points. This indicates that students performed about the same on a more difficult task, meaning that the new lab activity introduced this semester was helpful. Due to large changes in the rubrics and grading format for the final deliverables for Project 2, a direct comparison of grade distributions between the previous semesters was not conducted.

5 Limitations and Future Work

One key limitation of this work is that students work on different projects each semester, precluding the possibility of a perfect 1:1 comparison between semesters. Differences in the relative difficulty of projects, as well as differences between teaching assistants each semester introduce the possibility of large variances in student grade outcomes between semesters. This assembly lab activity will be improved and changed in three ways in the future.

First, we will move this lab activity to take place a few weeks later in the semester. Some survey evidence indicates that many students found the lab activity helpful. However, the lab activity was completed in the first week of the semester, while the students did not need to construct their projects until the sixth week of the semester. This large time gap reduced the effectiveness of the lab activity as the lessons learned were not immediately relevant and were forgotten by some students.

Second, we plan to improve this lab activity by creating structured and unstructured opportunities for students to revisit the assembly tasks. In the current version of the lab activity, students write their conclusions about the mechanisms and then do not revisit the assemblies. We will have students revisit this lab and the lessons they learned during project workdays later in the semester. Furthermore, we plan to facilitate unstructured opportunities for students to revisit this content by making these mechanisms available for students to see during office hours.

Third, we will continue to expand the set of demonstration mechanisms.

The source files for the mechanisms are available online at `https://drive.google.com/drive/folders/1xvzlKZ8OmDd1cDXjlqZouVdmf1_3W4zC?usp=sharing`.

6 Conclusion

This work presents a structured lab activity that was implemented in a 300-level mechanical design course at a large Midwestern R1 university. The lab activity consists of five different mechanical assembly tasks that are designed to give students practical, hands-on examples of good and poor design choices. In the first assembly task, students compare two different gear trains and see the impact of parameters like tooth size, backlash, and shaft supports on the overall quality of power transmission. In the second assembly task, students compare two different cam follower systems and see the importance of properly constraining the follower's motion. In the third assembly task, students compare different crank-slider mechanisms and see the impact of material choice and dimensioning on the smoothness of motion. The fourth assembly task focuses on linkages and joints, where students are able to compare well-constrained joints with joints that are made with loose tolerances. The final assembly task focuses on different methods of joinery, and encourages students to avoid overconstraining mechanical parts by showing box making techniques and having the students mount parts using pin-slider and overconstrained pin-pin connections.

To determine the efficacy of the lab activity for our class, we utilized two surveys and also looked to see if there was any change in the grade distribution of Project 1's "functionality" category. We found that at the midpoint of the semester, students thought that the lab activity was helpful, but they rated other resources as more useful than the lab activity. However, at the end of the semester, students rated this lab activity as the most helpful portion of the lab section. Overall grade distributions did not see significant changes, but it is possible that the project assigned in the Fall 2025, when this lab was piloted, was more difficult than previous semesters.

Altogether, it appears that students in this class felt that this was a valuable activity, although differences in projects and grading between semesters make it difficult to determine if there was a significant change in student performance as a result of the activity.

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7 Appendix

7.1 Mid Semester Survey

The following questions were asked to obtain the data for the mid-semester survey.

1. Feedback from Instructors, TA's and peers was helpful to make sure my dispenser functioned properly
2. My own research or knowledge was helpful to make sure my dispenser functioned properly
3. Lab 1 assembly [lab] activities were helpful to make sure my dispenser functioned properly

The raw data number of responses was:

Ranking	Feedback	Research	Assembly Lab
Strongly Agree	47	42	25
Agree	55	50	42
Neutral	28	26	36
Disagree	2	5	21
Strongly Disagree	5	4	3

7.2 End of Semester Survey

The following questions were asked to obtain the data for the end of semester survey

1. What do you feel are the most helpful things you learned in your lab section, and why?
2. What do you feel are the least helpful things you learned in your lab section, and why?

Responses were categorized. The raw data number of responses that was obtained was

Category	Helpful	Unhelpful
Lab 1: Assembly Lab	61	16
Lab 10/12:PVA/DFA	59	106
Lab 8: Motors	39	29
Lab 5:Curve Synthesis	33	14
Hands-on Activities	24	0
Other	13	20
Advice/Feedback	7	1
Low-Fidelity Prototypes	5	5
Project Applicable	3	4
Lab 2: HCD	1	19
None	0	14