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Including Hands-On Homework Problems in a Required Undergraduate Vibrations Course

Anne E. Martin, Pennsylvania State University

Anne Martin is an Associate Professor of Mechanical Engineering at the Pennsylvania State University. She joined Penn State in Spring of 2016. Prior to that, she was a postdoctoral associate in the Locomotor Control Systems Laboratory at the University of Texas at Dallas. She received her Ph.D. in mechanical engineering from the University of Notre Dame in 2014, receiving the Eli J. and Helen Shaheen Graduate School Award in Engineering for her dissertation research. In 2009, she graduated Summa Cum Laude from the University of Delaware with a bachelor's degree in mechanical engineering. Her research interests include modeling human walking and studying the impact of powered assistive devices on walking. She regularly teaches the required undergraduate vibrations course.

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Abstract

Many mechanical vibrations courses emphasize theoretical knowledge, but students often struggle to develop appropriate models and have a weak understanding of how mathematical models relate to the physical system they are modeling. Interacting with a physical model may help. To investigate this, I incorporated a few hands-on homework problems using inexpensive materials into the required undergraduate mechanical vibrations course for two consecutive semesters. Based on survey responses, students found the hands-on homework problems at least slightly useful but had some challenges with the logistics of completing the problems. Providing advance notice that the homework set included a hands-on problem reduced the logistical issues. It was unclear how much the problems improved student learning, with some metrics increasing slightly and others remaining the same compared to before the intervention. In summary, adding a few hands-on homework problems to a required undergraduate course without a lab component is feasible. Students found the problems somewhat helpful, and they may slightly improve learning, but not by a significant amount.

Introduction

The ability to appropriately model physical phenomena and understand the model's limitations is critical to practicing engineers [1], [2]. ABET also considers these skills to be important, as indicated by student outcome 1 (ability to solve engineering problems). Thus, students must learn to solve complex, poorly defined problems that appropriately capture a physical system's behavior [3], [4], [5].

Unfortunately, students often struggle to develop appropriate models [6], [7] and have a weak understanding of how mathematical models relate to the physical system they are modeling [2], [8]. Developing models requires students to identify an appropriate technique or topic to use and then to correctly apply it to the system of interest, both of which are challenging for novice engineers [6]. Interacting with a physical [9], [10], [11], [12], haptic [13], [14], [15], [16], [17], [18], [19], and/or virtual [20], [21] model may help address these challenges. These tools have been developed for a wide range of phenomena in multiple areas, including vibrations [22], [23]. When the activities are well designed, students generally appreciate them. Studies that have compared performance gains with and without physical interaction have typically found that the interaction improves student performance. Most commonly, the courses are also relatively small.

One course that could benefit from hands-on problems is vibrations. Most mechanical engineering programs require undergraduate students to take a course (or part of a course) on vibrations. These courses often emphasize the mathematical underpinnings of vibrations and may not include a formal lab component. For example, at my university, the majority of the course requires students to model single degree of freedom (DOF) systems and solve the corresponding linear differential equations. The more realistic problems for the course typically involve traditional mechanical systems such as beams, pumps, and turbines. Without a formal lab component, these problems are strictly modeling based. Not surprisingly, many students struggle to appropriately model the physical system and understand the model's limitations. Replacing a few traditional homework problems with low-cost hands-on problems may improve student learning. However, it is unknown how well incorporating these problems into a large class will work and if they will enhance student learning.

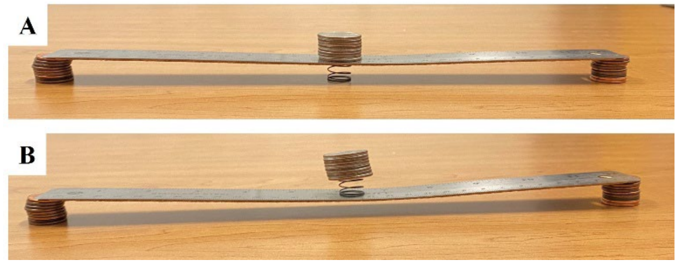


Figure 1: Parallel vs series problem. (A) The ruler and spring are in parallel because they have the same displacement. Most students initially think the ruler and spring are in series because they touch. (B) The ruler and spring are in series because the spring is between the mass and the ruler.

Methods

To investigate if including hands-on problems in large vibrations courses is feasible and improves student learning, I incorporated a few hands-on homework problems into the required undergraduate mechanical vibrations course for two consecutive semesters (Fall 2024 and Spring 2025). I assessed student impressions of the problems using a survey. To determine if the problems improved learning, I compared student performance from three semesters prior to the intervention (Fall 2022, Fall 2023, and Spring 2024) to the two semesters with the intervention. All research evaluation of the problems occurred after final grades were entered for the semester. The study received IRB approval.

Hands-on Problems

One problem had students calculate and compare the equivalent stiffness of beams arranged in parallel and series using a ruler, coins, and a compression spring (Figure 1) [24]. Briefly, students first measured the stiffness of the ruler using $k = \frac{W}{\Delta}$, where W is the weight of the stack of coins and Δ is the deflection of the loaded ruler. They then put the compression spring under the ruler, measured the deflection, calculated the expected deflection, and compared the values. Then they put the spring on top of the ruler, measured the deflection, calculated the expected deflection, and compared the values.

A second problem required students to measure and estimate the free response of a mass-spring system [25]. Briefly, students attached their phone to a standard extension spring hanging vertically. They then set the system vibrating and recorded the acceleration using their phone's built-in accelerometer and Matlab Mobile. Using provided code, they converted vertical acceleration into displacement. Using the given spring constant and damping, they calculated the expected response analytically and compared it to the experimental displacement.

A third problem required students to perform a frequency sweep of a forced one degree of freedom (DOF) system (Figure 2). Very briefly, students attached a motor to the end of a ruler, created a rotating unbalance using cardboard and a coin, and varied the motor speed. Students then compared the physical system's behavior with the expected behavior and estimated the natural frequency. This problem was only implemented the first semester because the setup was time consuming and data logging to the computer did not work consistently. Too much of the problem required effort not aligned with course objectives.

Logistics

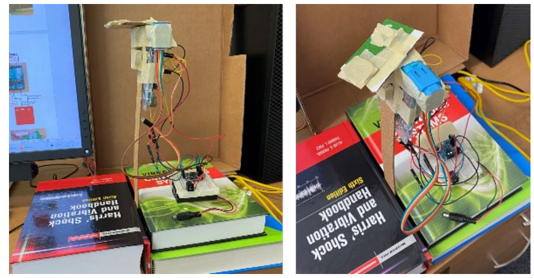


Figure 2: Set up for frequency sweep experiment with a rotating unbalance. When it worked, the system clearly demonstrated the peak in vibration near the natural frequency. However, correctly setting up and recording data was time consuming and unreliable, so the problem was only used one semester.

Each hands-on problem was assigned as one homework problem and was worth the same number of points as all other homework problems. The expectation was that they would take around the same amount of time (approximately 1 hour) as any other homework problem.

The problems used relatively inexpensive components that students could check out from the main Mechanical Engineering building plus household materials. Most sets of material could only be accessed when the office was open (usually weekdays before 4 pm) although there were a few sets available at all times. The second semester, I also provided students with links to purchase all material themselves if they preferred the convenience of doing the problems at home.

The first semester, I included a note on the homework assignment page that the homework included a hands-on problem. The second semester I also posted an announcement one week before the due date that the homework included a hands-on problem.

Surveys

Student impressions of the hands-on homework problems were assessed using surveys. Students who completed the survey received a negligible amount of extra credit. The survey questions included

- How useful were the mini-lab homework problems in helping you learn the following topics? [multiple choice with options a) Not at all useful, b) Slightly useful, c) Moderately useful, d) Very useful, e) Extremely useful]
  - Springs in parallel vs series
  - The relationship between a physical system and the response equations
  - How the system response changes as the forcing frequency changes (first semester only)
- Are there any improvements you would suggest for the hands-on activities? [free response]

Problem usefulness was assessed by counting the number of responses for each option for each question and then normalizing by the number of students who responded to the survey. Recommended improvements were grouped by theme and the number of times each theme appeared was counted and then normalized by the number of students who responded to the survey.

Student Performance Analysis

The effectiveness of the problems was assessed using project grading rubric data in areas related to the problems. Specifically, I evaluated

- Ability to calculate the equivalent stiffness of a system with multiple springs (Projects 1 & 2) – directly related to the first hands on problem
- Ability to calculate the response of a damped system with harmonic forcing (Projects 1 & 2) – related to the second and third hands on problem
- Overall quality of the discussion, including an evaluation of if their work is correct and how changing the model complexity impacts results (Projects 1 & 2) – indirectly related to all hands on problems
- Recognition that the analytical solution approximates the physical system (Project 2) – indirectly related to all hands on problems

Table 1: Number of students each semester.

Semester	Pre-Post	Enrolled Students	Consenting Students	Survey Responses
Fa22	Pre	69	46	NA
Fa23	Pre	81	55	NA
Sp24	Pre	89	60	NA
Fa24	Post	126	84	101
Sp25	Post	96	61	73

Using the rubric used to grade the project, each student was assigned a level for each evaluation area based on how well they performed. For each evaluation area, the number of students for each level was counted and then normalized by the number of students who consented to have their assignments included. For the first and last evaluation areas, three levels were used (correct/sufficient, incorrect/insufficient, and missing). For the other two evaluation areas, 6 levels were used (excellent/fully correct, very good, good, fair, poor, and missing).

Data from the three semesters before the intervention were compared with the data from the two semesters with the intervention. The projects and grading rubrics for each semester were very similar, but not identical. Students had to opt-in to having their data analyzed by emailing my grad student. Those who did received a negligible amount of extra credit.

Results and Discussion

In the semesters considered, class size ranged from 69 to 126 students and the number of students participating in research ranged from 46 to 101 (Table 1). 66% of students agreed to have their assignments included in the research analysis (67% pre-intervention and 65% post-intervention). 78% of the post-intervention students completed the survey.

Students found the hands-on homework problems at least slightly useful for learning the material (Figure 3), particularly for equivalent stiffness (42% extremely or very useful, 51% moderately or slightly useful) and understanding how models approximate reality (42% extremely or very useful, 52% moderately or slightly useful). Students in the second semester of the intervention found the problems more useful, possibly due to improved instructions and reduced logistical challenges.

The most common complaint about the problems had to do with logistics and obtaining the materials needed to complete the projects (32% of survey response, Figure 4). Particularly for the first semester, there were numerous comments about the challenge of going to the ME building when it was open because they had not planned for it. While I included a note on the homework assignment stating that it included a hands-on problem, this was not sufficient. The second

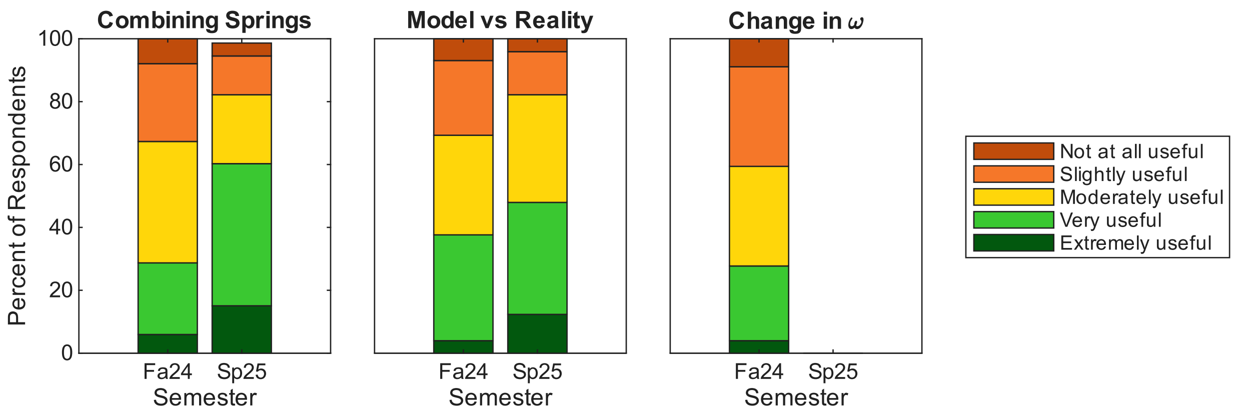
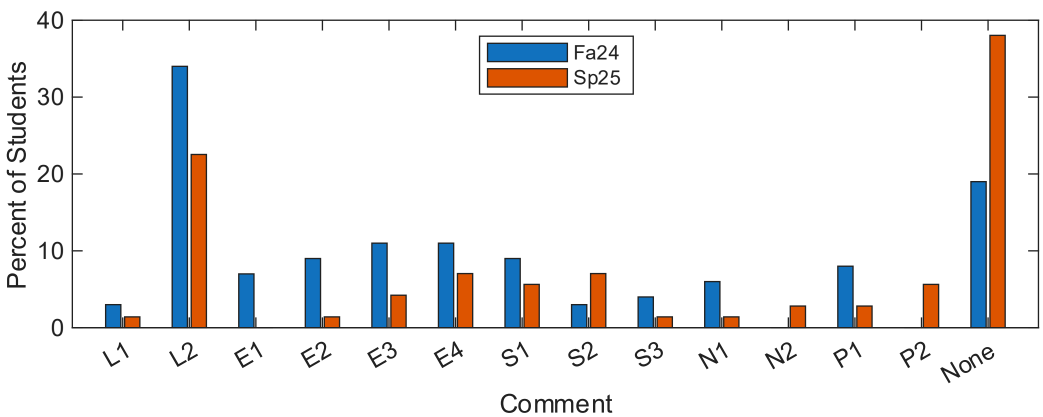


Figure 3: Student reported usefulness of hands-on problems. Most students found the problems at least slightly useful.



Code	Comment
L1	Give advance notice of hands-on problem
L2	Having to go to the ME building/difficulty obtaining materials
E1	Too hard to set up/set up should be easier
E2	Didn't work/too hard to troubleshoot
E3	More/clearer directions
E4	Too much time/effort, particularly for number of points
S1	Do in class or add a traditional lab section
S2	Make separate from homework
S3	Make online only (watch video or do virtually)
N1	Didn't like/not helpful
N2	Mild didn't like/not helpful
P1	Generally positive (liked, were helpful)
P2	Want more

Figure 4: Student comments on what could be improved for the hands-on problems. The most common issues were logistical. Going to the ME building when the office was open was challenging for many students.

semester, I posted an announcement a week before the due date stating that this week's homework included a hands-on problem. I also provided students with links to purchase their own material if they wanted to do the problem at home. This removed most, but not all, comments about having to go to the ME building. The second semester, the comments largely shifted to noting that they did not have coins easily available. Offering alternative weights may further improve the student experience.

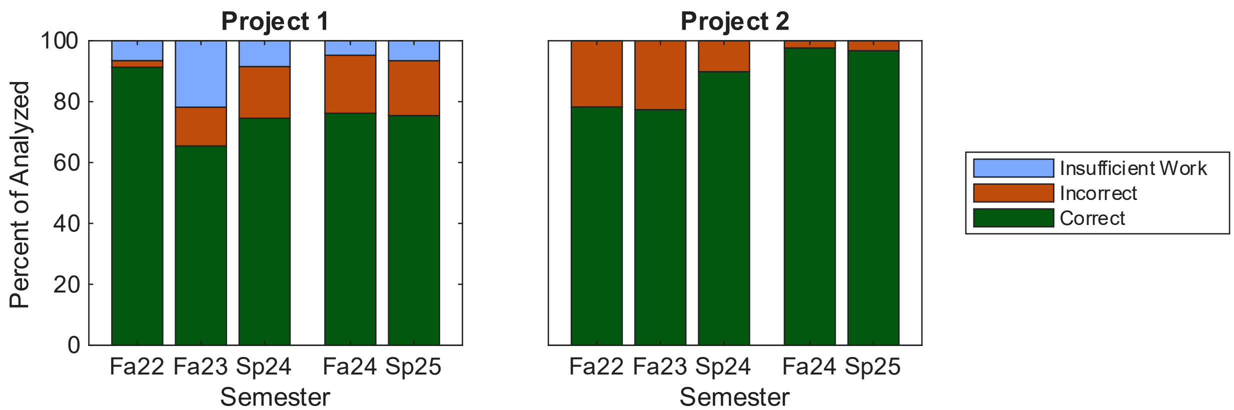


Figure 5: Student ability to correctly calculate the equivalent stiffness of a system with multiple springs. Hands-on problems were included in Fall 2024 and Spring 2025. It is not clear if adding hands-on problems increased student performance.

The second most common complaint was that the problems took too much time for not enough points (27% of survey responses). This primarily occurred during the first semester of the intervention, with comments roughly evenly split between having the set up be too time-consuming, having issues getting the problems to work, not understanding the directions, and wanting the problems to be worth more points. The second semester, I removed one problem that did not work for many students and added video demonstrations to help clarify instructions. Many of the set-up steps were challenging to clearly and concisely describe in writing but were much easier to show with a video. These changes appeared to significantly improve the student experience, reducing student comments about amount of time from 38% of students to 12%. The second semester, most comments in this area wanted the problems to be worth more points, rather than having issues doing the problem.

It is unclear how much the problems improved student learning. Average student performance in finding equivalent stiffness increased with the inclusion of the hands-on problems (Figure 5), but only for Project 2 (82% vs 97% correct) and not for Project 1 (76% vs 76% correct). The hands-

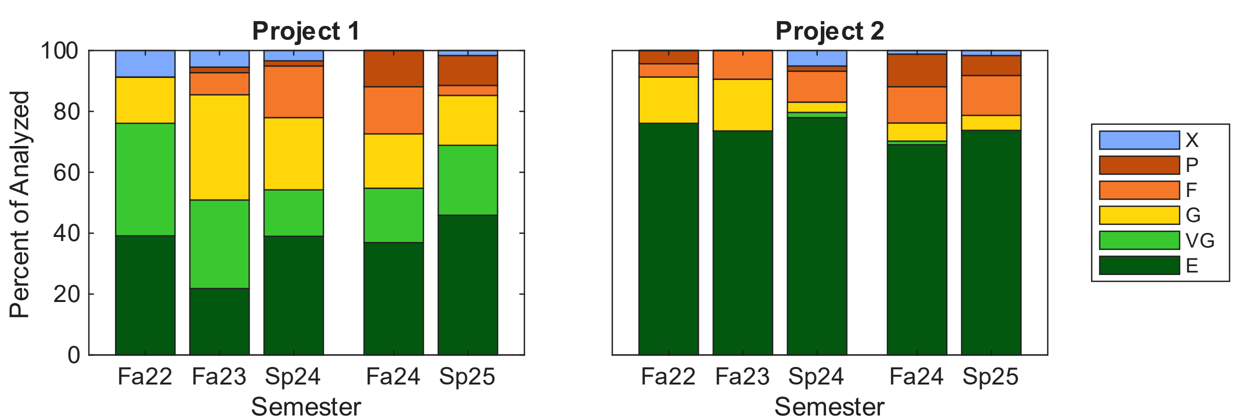


Figure 6: Student ability to correctly find the response of a harmonically forced one DOF system. Hands-on problems were included in Fall 2024 and Spring 2025. Student performance was characterized as **E**xcellent, Very Good (**VG**), **G**ood, **F**air, **P**oor, or Missing (**X**). The hands-on problems did not increase student performance.

on problems had minimal effect on student ability to calculate the response of a 1 DOF system subject to harmonic forcing (Figure 6). The overall discussion quality may have slightly increased after the intervention if Project 2 for Fall 2022 is neglected (percent rated excellent or very good: 36% vs 46% for Project 1 and 40% vs 44% for Project 2, Figure 8). The ratings for Fall 2022's Project 2 were much higher than all other cases, possibly due to a less refined rubric rather than significantly better student performance. In general, the discussion quality varied significantly between semesters, making it difficult to observe trends.

Student recognition that models approximate reality increased with the intervention (56% vs 72%, Figure 7) although this change occurred the semester before the hands-on problems were

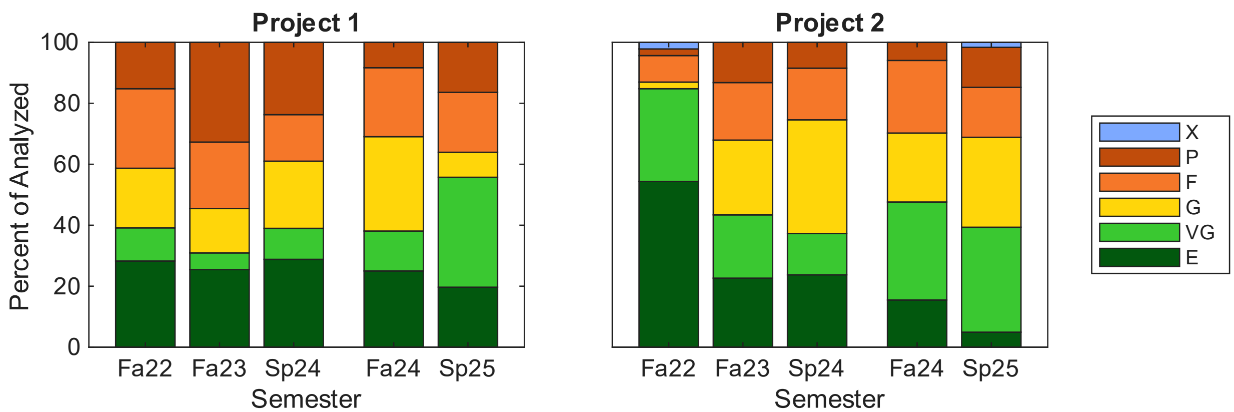


Figure 7: Overall quality of student discussion. Hands-on problems were included in Fall 2024 and Spring 2025. Student performance as characterized as **E**xcellent, Very Good (**VG**), **G**ood, **F**air, **P**oor, or Missing (**X**). The hands-on problems possibly slightly increased student performance, but variation between semesters makes it difficult to tell.

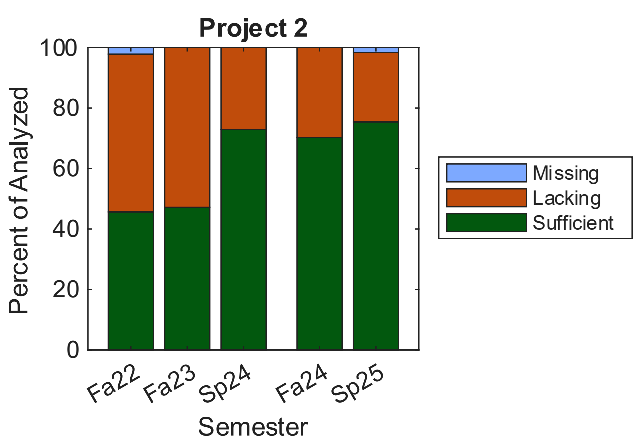


Figure 8: Ability of students to recognize that models approximate reality. Hands-on problems were included in Fall 2024 and Spring 2025. While the average percentage of students showing sufficient recognition increased after the intervention, the change occurred the semester before, so it is unlikely to be caused by the hands-on problems.

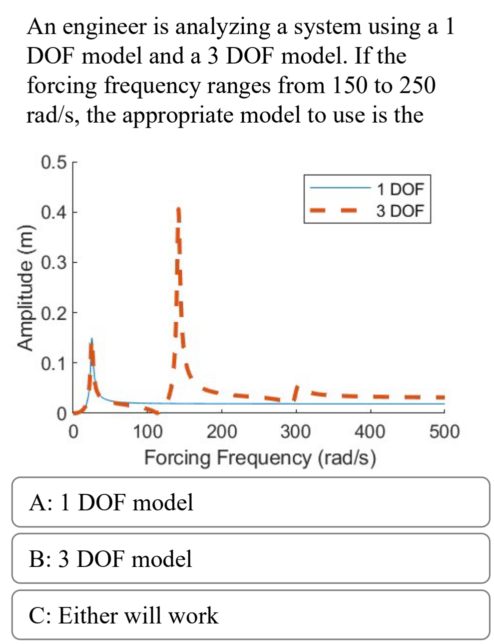


Figure 9: Top Hat question used to discuss the appropriate model to use.

added. In Spring 2024, the semester the change occurred, I added in-class Top Hat questions about topics students frequently got wrong on Project 2 when I introduced the project. This included a question about choosing an appropriately complex model (Figure 9). A significant percentage of students generally said we should use the simpler model because its performance is better over the range of operating frequencies. I then discussed that models approximate reality and that it is important to choose a model that captures the key behavior of your real system. It appears this question and associated discussion may have been more impactful for students recognizing that models approximate reality than the hands-on problems, at least in the context of the project discussion. Interestingly, I used a similar Top Hat question for Project 1 for all semesters. It appears students need to be reminded of this fact repeatedly throughout the semester, and that low-stakes quiz questions followed by discussion may be an effective way of doing so. The hands-on activities could also potentially be modified to more strongly emphasize this fact, although the current versions do require students to discuss the differences between the model and the physical system.

In summary, adding a few hands-on homework problems to a large required undergraduate course without a lab component is feasible. It is important to actively notify students in advance that an assignment includes these activities. Students found the problems somewhat helpful, and they may slightly improve learning, but not by a significant amount.

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