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Mobile, Hands-on Experiments Designed to Enhance Student Comprehension, Engagement, and Collaborative Learning

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Introduction

Experiential learning can make engineering concepts come to life, giving students a real-world confirmation of the theory and concepts from lecture classes. All too often, however, undergraduate laboratory classes fall short of enhanced learning and are instead more notable for student dissatisfaction and/or frustration [1], [2], [3]. There are several reasons for this problem. First, organized laboratory classes are often used to meet numerous student outcomes such as those comprising ABET student outcomes (1) – (7) [4]. Second, organized laboratory classes are often taught separately from theory classes, leading to a disconnect from pre-requisite courses and uneven understanding among the student cohort. Third, organized lab classes often involve teamwork, without specific instruction or guidance on how to work effectively, how to divide up tasks, and how to handle conflicts.

Due to advances in microprocessors and portable data acquisition devices, widespread student use of laptop computers, growing availability of affordable sensors, and the emergence of versatile 3D printers and benchtop CNC machining, there is an unprecedented opportunity to bring hands-on experiments out of the centralized labs, and into lecture classrooms, and even student dorm rooms. Portability of the platforms can obviate the need for dedicated lab space and equipment. Furthermore, small, portable hands-on platforms can be designed to target one or two specific learning objectives. This ensures that the concepts involved in the hands-on exercises are tightly coupled to the theory delivered in lectures and assessed in homework assignments.

We will describe progress in the development of new hands-on learning experiences, and we will review refinements and extensions of hands-on learning experiments developed earlier and described in [5], [6], and [7].

Two-Degree of Freedom Platform

Two-degree of freedom (2DOF) systems are studied in a variety of engineering fields and in several different courses. Examples in the ME and AE curricula are system dynamic classes and vibration classes. They can be thought of as very simplified models of mechanical vibratory systems such as quarter-car vehicle models or two-story seismic building models. Hands-on learning with single degree of freedom (SDOF) systems can be as simple as suspending a mass on a spring, but SDOF systems cannot exhibit vibratory modes, which is a key objective of the experiment under development. Two degree of freedom portable vibration models are more difficult to realize than SDOF systems, especially if quantitative measurements are desired. And while multi-degree of freedom systems such as guitar strings have been studied (eg. [8] and [9]), a lumped, 2DOF system is desirable because students can view it as from an elementary modeling standpoint and can compare theory with experiment.

There has not been much prior work in the development of low-cost, simplified portable 2DOF hands-on learning platforms. A notable exception is the work of Tekes and co-workers [10], [11]. Tekes designed innovative SDOF and 2DOF vibratory systems composed of parts that were 3D printed. In her rotational, 2DOF system, angular sensors were embedded in the system and could be read by an Arduino and DAQ. However, their vibratory work did not discuss experiments using forced harmonic excitation, which is an important goal for the present study. Morgan, et al. [12] describe the use of several vibrations experiments for classroom use. The SDOF, free-response experiment appears to be hands-on for use by students, while the forced-response SDOF and 2DOF experiments are more for use in classroom demonstration mode. Pardue and Darvennes [13] discuss the use of an air-track-based vibration system in their vibration class. Air tracks such as those sold by Pasco [14] are often used in classrooms and in dedicated laboratory settings. With a 2 meter air track, one can demonstrate SDOF and multi-DOF free and forced response. The devices are typically fairly large and require AC power for the air source (vacuum cleaner) and for the motor excitation system. Vibrations experiments using other commercially available turn-key apparatuses may be found in Ruhala [15]. The goal of the present research is to drive down the cost and complexity of the device so that it can be used by students at their desks or in their dorm rooms, requiring only battery power.

For lumped, translating systems, harmonic excitation is most easily accomplished through oscillatory motion. An early prototype developed by the authors is shown in Figure 1. The figure shows a thin beam mounted vertically in a clamped-free (cantilever) manner. The first mode of the beam can be viewed as an approximate SDOF system in the frequency range around the first resonant frequency. A design goal was to have minimal physical contact with the beam, which posed a significant challenge. An electromagnet was considered, but ruled out due to the power requirements which made portability of the platform a problem. Instead, a variable-speed DC motor was used to supply rotation to a slider-crank mechanism, causing the slider to execute approximate harmonic motion. Slider cranks were also used in [12], with the slider attached to the vibratory system by means of a spring. The spring connection to the motion excitation is usually termed a base-excited or seismic excitation system.

In the prototype explored by the authors, driving forces were imparted to the beam through an arrangement of permanent magnets, oriented to oppose each other (north to north or south to south). As the magnet on the slider crank moved towards and away from the opposing magnet mounted to the beam, oscillatory forces were imparted to the beam. The magnets, it was felt, would have a much less intrusive effect on the system dynamics.

Although the slider crank mechanism worked relatively well, the translational motion of a slider-crank is known to have a 2nd harmonic present, which gets less significant as the ratio of the follower length to the crank arm gets larger. There were also limitations on how small the crank arm could be, and on the overall size of the device because of the need for a high follower length. For that reason, the slider crank was replaced with a *Scotch yoke* arrangement, as seen in the experimental apparatus in Figure 2. A Scotch yoke was also mentioned in [13] to drive the

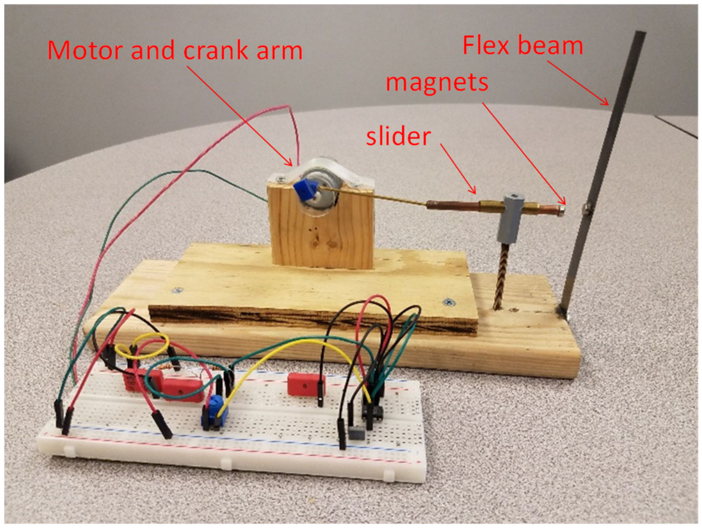


Figure 1. Single-degree-of-freedom prototype

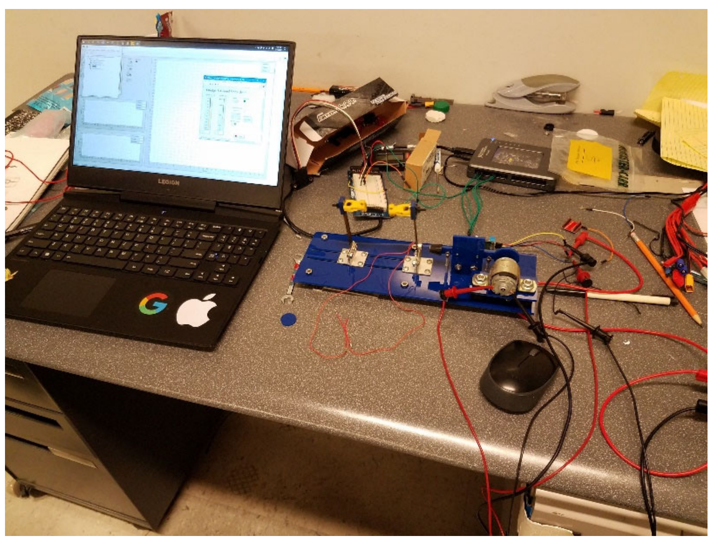


Figure 2. Experimental 2DOF platform implementing Scotch yoke mechanism for oscillatory force

base-spring of the last mass on the air track. Figure 3 shows a schematic of the 2DOF system, with various parts labelled.

For simplicity and ruggedness, vibratory motion of the beams was measured using guitar pickups, similar to the design used for portable string experimental platforms [8], [9]. An alternate approach to be considered is to use electrical resistance strain gauges attached near the roots of the beams to measure the bending strain using simple, desktop instrumentation developed for static beam testing [6].

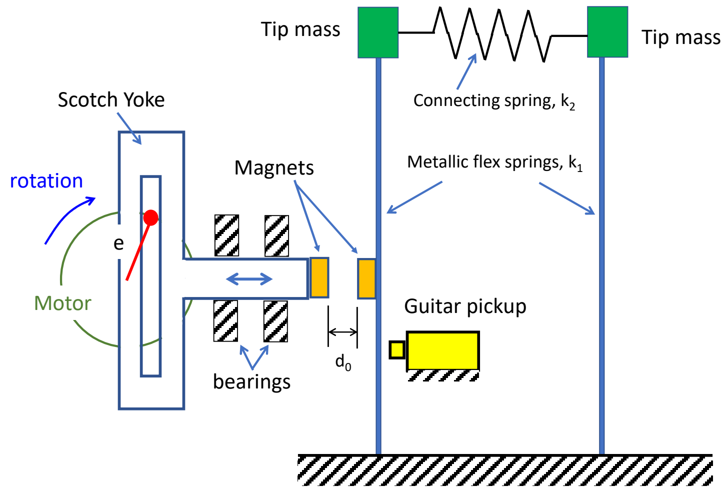


Figure 3. 2DOF schematic used for modeling purposes

One of the advantages of the developed translational 2DOF system is the simplicity of the model used to describe its behavior. The model can be developed by students taking system dynamics, and the response can be analyzed and simulated using built-in MATLAB tools. The displacement of the two masses in Figure 3 are denoted x_1 and x_2. The magnetic force is assumed to be applied at a location z_m along the beam span and the deformation shape of the beam is approximated by the static cantilever beam shape function $\phi(x) = 1.5(x/L)^2 - 0.5(x/L)^3$. Note that $\phi(0) = 0$ and that $\phi(L) = 1$. The undamped equations of motion can be written

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{Bmatrix} + \begin{bmatrix} (k_1 + k_2) & -k_2 \\ -k_2 & (k_1 + k_2) \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} = \begin{Bmatrix} F_m \phi(z_m) \\ 0 \end{Bmatrix}$$

where F_m is the magnetic force exerted on the beam at location z_m. Note that a small amount of proportional damping is also present but is not shown in the equation of motion above. The magnetic force has an inverse-square relation to the distance between the two magnets

$$F_m = \frac{F_0}{(d_0 + x_1 \phi(z_m) - u)^2}$$

where d_0 is the nominal magnet separation distance and u is the harmonic displacement of the excitation magnet imposed by the Scotch yoke and given by

$$u = e \cdot sin(\omega t)$$

where e is the crank length. A key assumption is that the displacement of the two magnets is small relative to the nominal separation distance, d_0. When that is the case, it can be shown that F_m is approximately harmonic. As d_0 gets smaller, the presence of a 2^{nd} harmonic in the excitation becomes more and more pronounced. A MATLAB simulation of beam amplitude versus frequency ω is shown in Figure 5 for a nominal set of physical parameters. The presence of the two natural frequencies is clearly visible, with one peak being close to 11 Hz and one close to 30 Hz. The presence of a null or *absorption frequency* around 23 Hz is also seen. It may be noted that with the parameters under consideration, there is evidence of a slight 2^{nd}-harmonic resonance around 6 Hz. From a pedagogical standpoint, this may be undesirable for sophomore or junior level classes, where agreement of theory and experiment helps students build confidence in their understanding. Hence, care will need to be employed in choosing d_0 in the final design to be large enough to avoid this anomaly, but small enough to get adequate excitation of the system.

The experimental system has been studied using both free response and forced response. A sample of free response plots from the experiment is shown in Figure 5. Note that the time response shows a decaying amplitude, from which students can estimate a damping ratio. In the frequency domain, the spectrum of the response clearly shows two dominant frequencies which are the natural frequencies of the system.

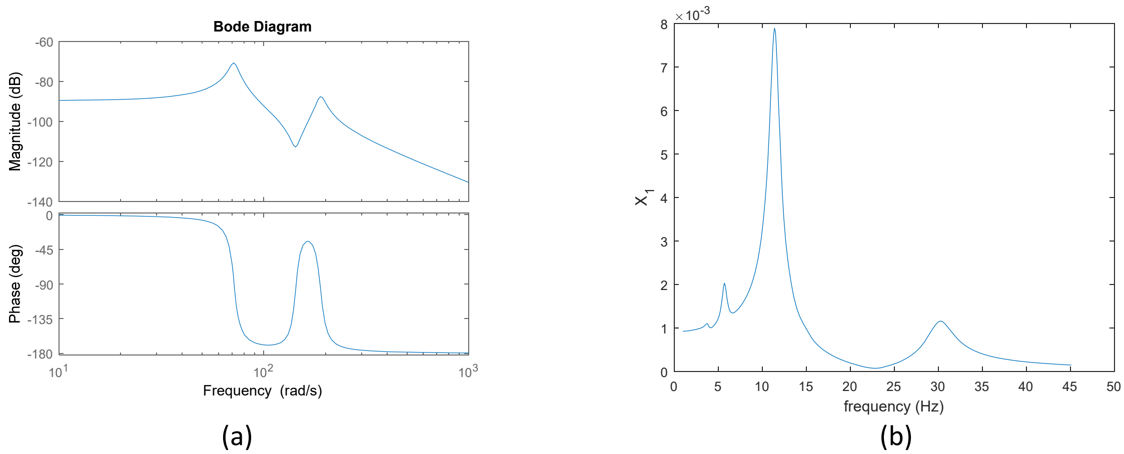


Figure 4. Frequency-response plots. (a) Bode plot obtained using a linearization of the magnetic force function and (b) simulation results using steady-state response amplitudes at a range of forcing frequencies.

Progress on Other Hands-On Platforms

To date we have developed a number of hands-on learning platforms [5], [6], [7], [9], [16], [17], 18]. In [6] and [7], the authors presented a bending beam apparatus that could be used by undergraduate students in the ME, AE, and CE disciplines. We continue to refine this platform with the goal of making it versatile and cost-effective. This includes refinement of an optical measurement system (Figure 6) to measure beam tip vertical and lateral displacements and twist rotations. The goal is for students to be able to acquire accurate quantitative measurements with resolutions of 0.05 mm using only an inexpensive 720p or 1080p webcam connected to their laptop.

We also continue to develop Design, Build, Test (DBT) thin-wall beam projects that can be carried out using 3D printed beams with various open and closed thin-wall cross sections. For example, in the classroom students learn that a beam with an unsymmetrical cross section will not only deflect in the direction of the load but also in the lateral direction as well. In the related DBT project, they are challenged to design either an open- or closed-section thin-wall

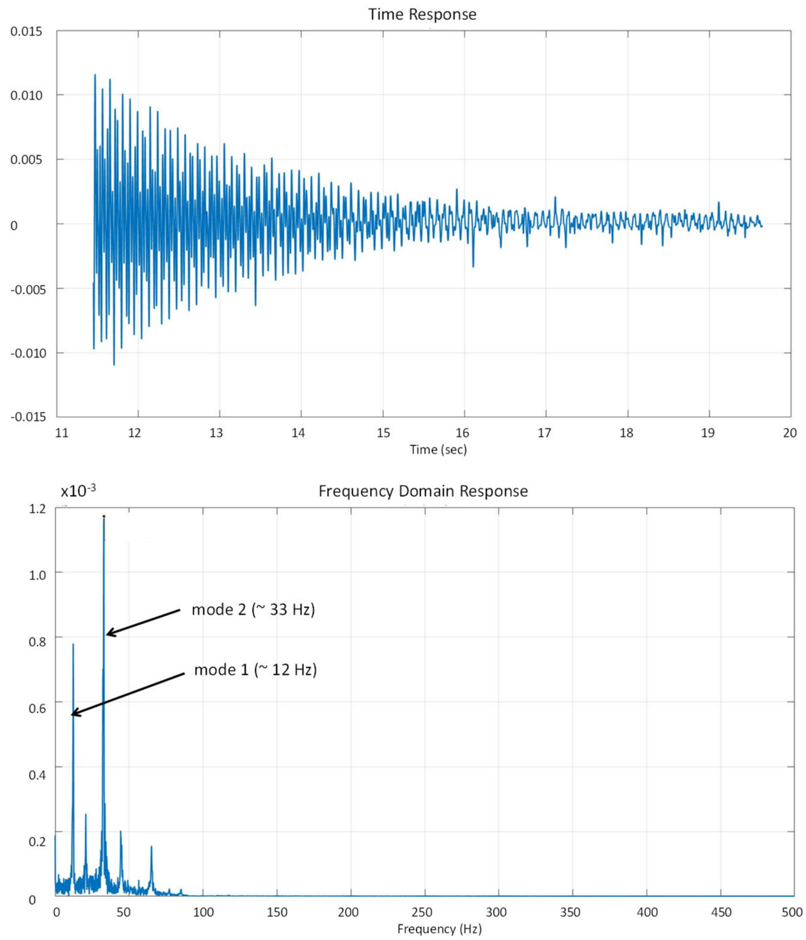
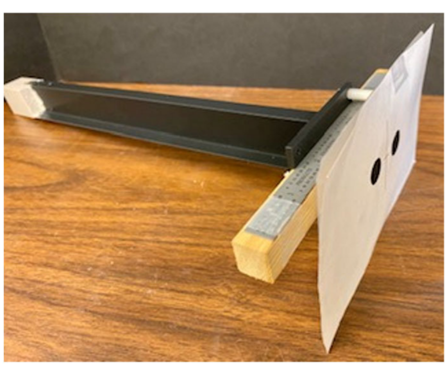
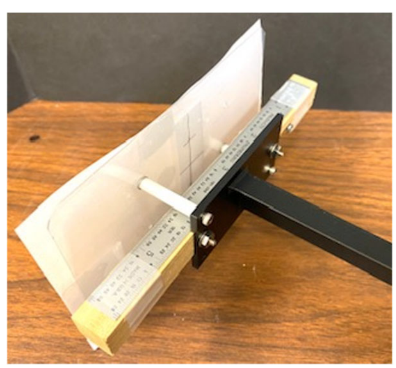


Figure 5. Experimental free response results. (a) time domain and (b) frequency domain



(a) Thin-wall Z section with tip optical tracking target.



(b) View showing attachment to tip plate (crossbar is not used).

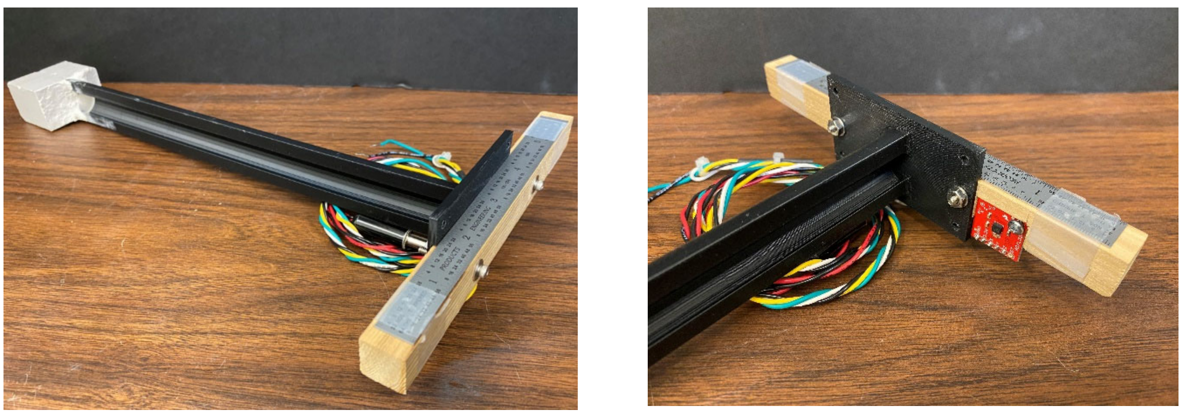
(c) Inexpensive webcam and tripod mounting.

Figure 6. Example DBT thin-wall Z section designed to achieve high lateral deflection under vertical tip load.

cantilevered beam to achieve a specific lateral deflection under the application of a vertical tip load.

The students also learn in the classroom that the shear center is the location on the cross section through which the lateral load must be applied to avoid introducing any unwanted twisting (which in open-section thin-wall beams can lead to excessive deformation due to their extremely low torsional stiffness). In the related DBT project, they must design both an open- and a closed-section thin-wall beam, calculate the shear center location, and then measure the location in a tip-loaded cantilever with the same cross section. Figure 7 shows a sample design of an open D section, and Figure 8 shows solid model designs for some of the thin-wall sections that have been printed and tested by students.

The DBT procedure has been developed, but the authors were not able to run the exercise due to Covid disruptions during the past academic year.



(a) Beam with white plaster root clamping block on left and on right the tip crossbar for applying torque using a hanging fixed weight.

(b) View showing crossbar attachment to tip plate and 3 axis inertial accelerometer used to measure crossbar tilt.

Figure 7. Example DBT beam design for shear center measurement.

Progress on Teamwork Observations

A final consideration in creating an effective learning experience for students is the question of team dynamics. When performed in group or team settings, the effectiveness of hands-on learning relies critically on students' ability to work together, exchange thoughts, and share equally in applying their knowledge to their experimental task [19]. At the authors' institution, the hands-on experiments are usually performed by small teams of students (2 or 3-person teams) that are formed based alphabetically or on seating proximity. At times, such impromptu pairing causes problems for a number of reasons. when teams do not function well, they can be the source of considerable stress and feelings of exclusion. This is especially true in engineering for female students and students from underrepresented minorities (URMs) [20], [21], [22]. The authors are particularly interested in Diversity Equity and Inclusion (DEI) issues that can

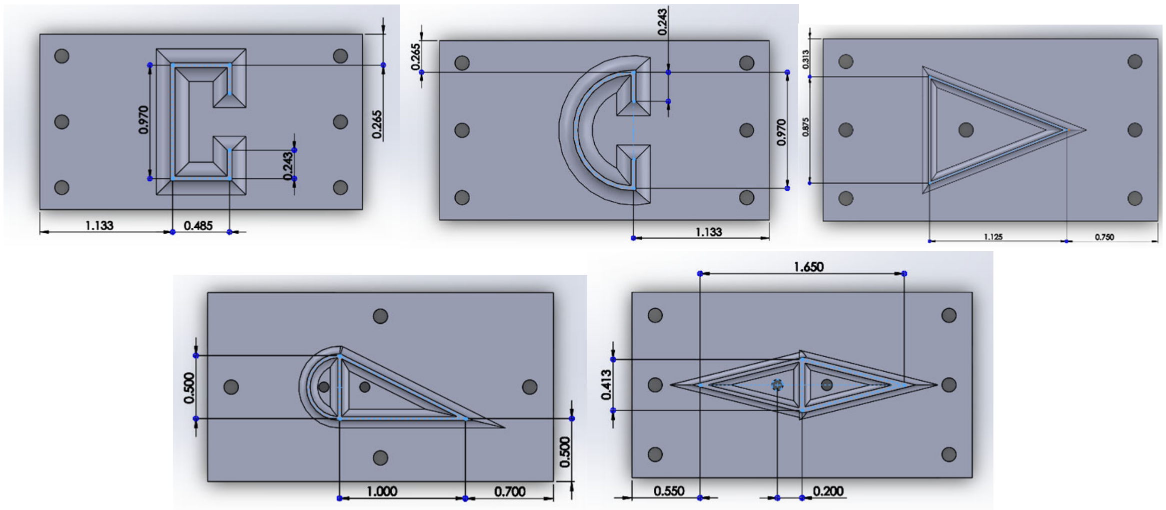


Figure 8. Example solid model cross sections showing integral tip plate to attach crossbar or optical target for tracking 2D tip deflection using a webcam.

undermine the effective learning in these teams when female or underrepresented minorities are involved. Since the teams are transient (i.e., formed expressly to perform a task within the context of a single, 50-minute class) there isn't time to include teaming instructions at the beginning of each exercise. Thus, policies and procedures are necessary to promote collaboration, and the training must be intentionally designed to be as portable as the experiments themselves.

Unfortunately, due to Covid restrictions, it has not been possible to conduct additional experiments or assessments this year. The experiments could not be carried out while adhering to the social-distancing guidelines for safety. Furthermore, most lecture classes at the authors' institution ran in "hybrid mode," which means that only one half or fewer of the enrolled students were present in each particular lecture. Observational studies of team dynamics and the development of mitigation strategies aimed at creating inclusive learning environments will resume when Covid restrictions are fully lifted in Fall 2021.

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