Enhancing Undergraduate Engineering Education through Experiential Learning Activities in Statics

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Abstract*– Statics, the most fundamental engineering mechanics component of the curriculum for nearly every engineering major is typically taken during the sophomore year and, for many, represents their first true engineering course. Students draw from knowledge taken from the arenas of math and physics and learn to predict how systems of forces will behave. Even though the concepts represent the basic application of their academic core, we have viewed first hand a high percentage of students struggling with many of the concepts; possible reasons for which are discussed in this paper. Presented herein are new, innovative, hands-on experiential learning activities that include physical representations of traditional Statics problems, each specifically tailored to increase a student's grasp of the material and enhance their problem-solving skills. These experiential activities have been proven to be highly effective. They have also been designed to be portable, affordable, and deployable in a manner that does not require additional lab time and in no way detracts from valuable lecture and class time thus preserving the current credit hour count. Eight different activities covering the following topics are detailed in this paper: two-dimensional particle equilibrium, pulleys, equivalent systems, two-dimensional rigid body equilibrium, frames, cables subject to discrete loads, fluid pressure, and friction. Also present are the results demonstrating the effectiveness of the experiential learning activities with regard to surveys gauging student acceptance and perceived value. Overall, the experiential learning activities employed by our school enhance the education of the students in Statics and therefore provide them with a stronger starting position for subsequent courses in Engineering Mechanics. It should also be noted that these activities are well suited for outreach programs to demonstrate application of STEM to potential upcoming engineers.

Keywords—Engineering Education, Undergraduate Education, Statics, Experiential Learning, Hands-on.

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Abstract– ***Statics, the most fundamental engineering mechanics component of the curriculum for nearly every engineering major is typically taken during the sophomore year and, for many, represents their first true engineering course. Students draw from knowledge taken from the arenas of math and physics and learn to predict how systems of forces will behave. Even though the concepts represent the basic application of their academic core, we have viewed first hand a high percentage of students struggling with many of the concepts; possible reasons for which are discussed in this paper. Presented herein are new, innovative, hands-on experiential learning activities that include physical representations of traditional Statics problems, each specifically tailored to increase a student's grasp of the material and enhance their problem-solving skills. These experiential activities have been proven to be highly effective. They have also been designed to be portable, affordable, and deployable in a manner that does not require additional lab time and in no way detracts from valuable lecture and class time thus preserving the current credit hour count. Eight different activities covering the following topics are detailed in this paper: two-dimensional particle equilibrium, pulleys, equivalent systems, two-dimensional rigid body equilibrium, frames, cables subject to discrete loads, fluid pressure, and friction. Also present are the results demonstrating the effectiveness of the experiential learning activities with regard to surveys gauging student acceptance and perceived value. Overall, the experiential learning activities employed by our school enhance the education of the students in Statics and therefore provide them with a stronger starting position for subsequent courses in Engineering Mechanics. It should also be noted that these activities are well suited for outreach programs to demonstrate application of STEM to potential upcoming engineers.***

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I. Introduction and Literature Review

The concepts and calculations learned in Statics class, the most fundamental of courses in engineering mechanics, are paramount to learning additional and advanced topics throughout the engineering curriculum. Often, in their efforts to communicate the material, instructors, searching for illustrations and demonstrations to convey even the most simple of subjects, turn to physical examples or "hands-on" exercises. The effective implementation of hands-on exercises to facilitate the communication of the ideas is challenging but can be illuminating to the student and, more so, help to build enthusiasm toward the subject matter. By engaging students while strengthening the connections and associations to previous, real world, experiences [1] students are able to internalize the concepts and effectively make them part of their problem solving tool box.

Regardless of results, instructors in pursuit of excellence and innovation are drawn to ways of explaining Statics that solidify concepts [2] and reach today's students who, for many, do not possess the practical hands-on manual experience common to construction or shop-type projects where one might unknowingly develop an intuition for concepts in Statics. So it follows that a value, to both the instructor and the student, is realized when hardware configurations where forces are indeed real and palpable to students [3] are made available to explore. There is no substitute for physically experiencing the fundamentals of Statics in a manner where the physical world is the authority [2].

The use of experiential learning in statics is not new. Other authors [2]-[6] have developed hands-on activities that range from a manipulative truss model to help students conceptualize truss analysis [5] to three-dimensional particle equilibrium using electronic load cells [6]. In this paper, we present some new hands-on activities and more importantly, present activities that allow the students to easily compare measured and calculated values. This comparison gives proof to the students that they can use math and science to predict how things behave, therefore illustrating the value of engineering design. This paper provides two new and significant findings for experiential learning activities in statics: 1) setup of activities that allow the students to easily measure angles and forces and 2) the ability for the students to see that the calculated values match the measured values. Additionally, this paper provides the setup and implementation that other educators can follow or easily adapt to other courses.

To assess the effectiveness of the activities, some anecdotal data from student surveys is presented. The principal emphasis of the paper however is to illustrate the setup of the activities and the applicability to traditional problems addressed in Statics courses. A list of activities are described in the next section and is followed by student survey results and conclusions.

II. Setup of Activities

The successful implementation of hands-on activities is key to reaching the goal of student learning. Illustrating even the most compelling of subjects can be fruitless if the exercise does not show strong connections and direct, tangible correlations with typical textbook type problems and real

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world applications. This section provides details for the equipment and setup configurations for eight experiential learning activities that have received good feedback and wide acceptance from both students and instructors. Also included are the follow-up questions that aim to reinforce key concepts for each topic and make the exercises complete.

One of the most popular tools used in many of the activities is a device called a *tension protractor* distributed by PASCO Scientific shown in Fig. 1 below. The device is very helpful and illustrative and allows students to easily ascertain both the direction and magnitude of a force in an attached string. A function that lends itself nicely to a myriad of different applications in Statics.

Fig. 1 PASCO Scientific Tension Protractor (Image Courtesy of PASCO Scientific)

The actual execution of the activities allows students to explore the equipment at their own pace without using valuable lecture time or requiring a dedicated lab session. Our approach has been to deploy the activities as a self-guided exercise during recitations or office hours and allow students to work independently or as part of a small group. Students are provided a set of instructions in a format similar to a typical slide presentation and usually spend around 30 minutes to complete each activity. The first of these activities, Two-Dimensional Particle Equilibrium, is discussed below.

A. *Two-Dimensional Particle Equilibrium*

The two-dimensional particle equilibrium activity requires two tension protractors, two table clamps (not shown), and a frame consisting of two vertical steel rods and a cross member to create the setup shown in Fig. 2. The materials and construction of the frame itself is less important than the flexibility it allows. The design of the frame is intended to allow the tension protractors to be moved to varying horizontal and vertical positions depending on the problem being illustrated and the goals of a particular exercise.

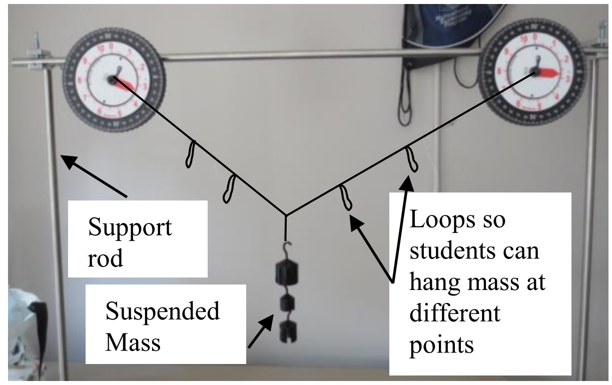

Fig. 2 Setup for the Two-Dimension Particle Equilibrium Activity.

Activities such as the exercise describing two-dimensional particle equilibrium have been developed from the guidance documents that accompany the PASCO Scientific equipment. In this activity students are asked to record the force and angle from each tension protractor for a mass suspended first, at a location of their choosing, then followed by several different prescribed locations. Students select a value for a suspended mass and choose its location. Based on their observations of the tension protractors, students are asked to make calculations and thoughtful predictions about changes in the system that would result from the relocation of the mass. The skills developed by students during this exercise include transferring the physical observations and direction of the forces to a FBD and calculating its Cartesian components. Students are then asked to calculate a tension in each string based on observed angles and the value of the suspended mass. A comparison can then be made between the calculated value and the value read from the tension protractor. If the measured and calculated values are within 5% of each other, the student has successfully used math and science to predict the physical behavior of the system and the connection between the physical world and engineering predictions is reinforced. If the student is unsuccessful, rechecking and repeating, a worthwhile endeavor in and of itself, is required.

Follow-up concept questions include:

1) True/False: The force in the string on each side of the mass is a function to the mass supported by the cable? and,
2) The resultant of the forces in each cable is straight up, straight down, to the left, or to the right?

The problem illustrated in the two-dimensional particle equilibrium hands-on activity is purposely configured to be similar to typical problems from Statics textbooks. For example, the problem shown in Fig. 3 is Fundamental Problem 3.1 from Hibbeler's Statics textbook [7]. After completing the activity, the problem becomes colored with real world experience and students are better

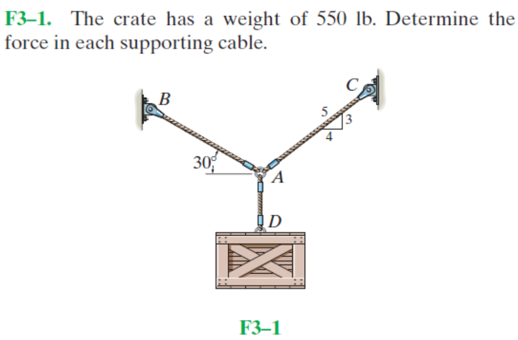

Fig. 3 Problem from Hibbeler's Statics14th Ed. [7] that is similar to the Two-dimensional particle equilibrium activity.

equipped to address the concepts and calculations applicable to this particular problem. It is expected that students will gain insight into drawing the appropriate FBD when attempting to predict reality; a skill which may not be completely developed by solving the problem in the text alone.

B. Pulleys

The hands-on activity designed to illustrate the behavior of pulleys utilizes two tension protractors, two table clamps, two steel rods, and a pulley as shown in Fig. 4. The pulley is made of light weight plastic commonly available at a local hardware store. Experience has shown that selecting a pulley that is relatively small, lightweight, and with little friction reduces errors thusly increasing confidence and acceptance of the concepts being explored.

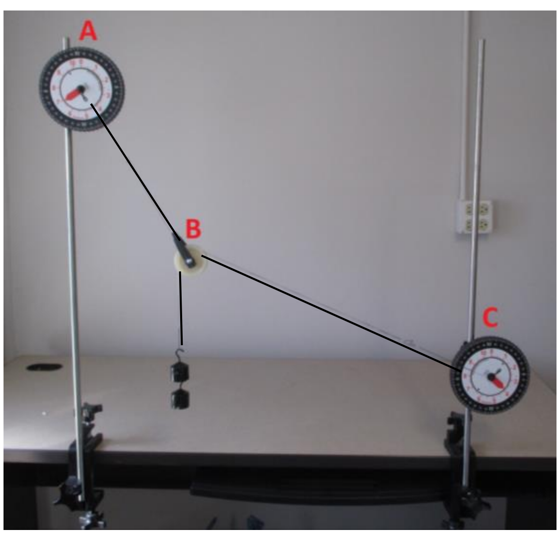

Fig. 4 Setup for the Pulley Activity.

An accompanying exercise was created to give students insight into the key concepts necessary to solve systems involving pulleys. This activity challenges students to predict the tension that will result in segment AB when a mass is suspended from a string passing thru the pulley at B and secured to the tension protractor at C. Students select the mass and are allowed, even encouraged, to change the geometry of the system by moving the tension protractors up or down along the left and right support rods. Observations for the tensions and angles in each segment, resulting from the suspended mass, are recorded and compared to calculated values.

Specifically, students are asked to treat the angle and tension in segment AB as an unknown and to draw a FBD that correctly describes the condition. The equilibrium equations are then used to determine the angle and tension in segment AB. Students are subsequently asked to compare their measured and calculated values. If observed and calculated results are not within 5% of each other, the students are required to check their measurements, revisit their calculations, and revise as necessary.

Follow-up concept questions include:

1) Why is the tension in string AB not equal to twice the tension in the cable supporting the mass?

2) If the angle of the string at C decreased (moved closer to being horizontal):

The tension in string BC would _________(increase, decrease, stay the same) and,

The tension in the string AB would _________(increase, decrease, stay the same).

A similar problem from Hibbeler's 14th Ed. [7] is shown in Fig. 5.

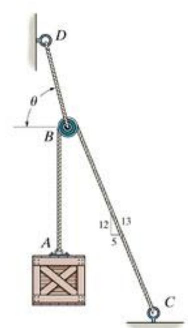

Fig. 5 Problem from Hibbeler's Statics14th Ed. [7] that is similar to the Pulleys activity.

C. Equivalent Systems

The equivalent systems activity requires two tension protractors, two table clamps, two steel rods, a meter stick, string, and masses of known value to create the setup shown in Fig. 6.

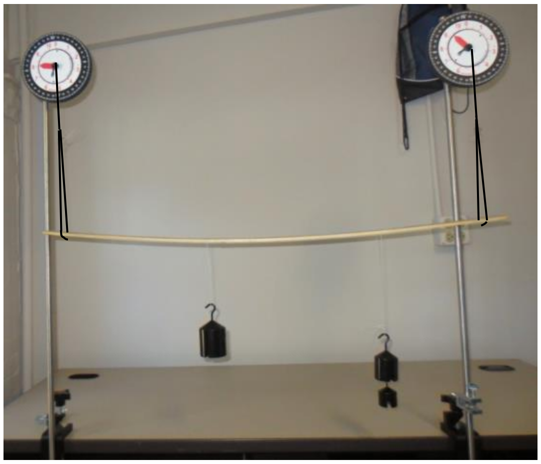

Fig. 6 Setup for the Equivalent Systems Activity

The equivalent system activity was created by the authors to help students understand how different loading configurations result in similar end reactions by creating a configuration of their own. For this activity the students are asked to record the force observed for each tension protractor, the location of each mass, and the value of each mass. Students pick the value of masses to hang in two or more unique locations of their choice. Note that the strings supporting the meter stick on each end are vertical and that the meter stick is horizontal.

The students are then asked to replace the original loading as shown in Fig. 6 with an equivalent resultant force and specify the location to yield the same end reactions. Students then physically place the calculated equivalent resultant force at the calculated location. If the force in the tension protractors is the same as the original loading case, they have successfully calculated the equivalent system. Note that any error in this experiment occurs equally in both the original and equivalent system and the weight of the meter stick can be included or excluded as it also has an equal effect in both the original and equivalent system.

The follow-up concept questions include:

1) An equivalent system will (always/sometimes/never) have the exact same support reactions as that of the original system.

2) (True/False) The forces applied to the original system are sometimes equal in magnitude and direction to the forces applied in the equivalent system.

3) (True/False) Taking the moment about any point in the original system will give the exact same magnitude and direction of the moment about that same point in the equivalent system.

A similar problem from Hibbeler's 14th Ed. [7] is shown in Fig. 7.

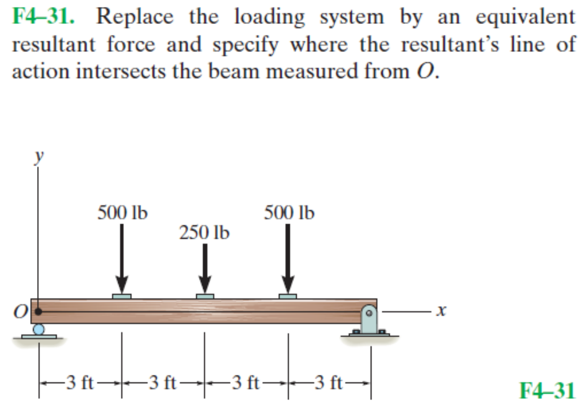

Fig. 7 Problem from Hibbeler's Statics14th Ed. [7] that is similar to the Equivalent Systems activity.

D. *Two-Dimension Rigid Body Equilibrium*

The two-dimensional rigid body equilibrium requires a similar setup as shown in Fig. 6. In this exercise students choose locations to place multiple masses along the meter stick. Students pick the value of each mass to hang at one or more unique locations of their choice, provided that the location is not a single mass at the midpoint of the meterstick. Students are asked to record the tension observed in each tension protractor, the location of each mass, and the value of each mass.

The students are asked to use two-dimensional equilibrium and an associated FBD to solve for the force in each support string attached to the tension protractors. Students are asked to include the weight of the meter-stick and to compare the measured and calculated values in the support strings. Typical errors are less than 5% when reasonable care is taken in recording values and when calculations are done correctly.

The follow-up concept questions include:

1) The system is _______(conditionally /unconditionally) stable and statically _____ (determinate/ indeterminate).

2) (True/False) The center of the mass of the stick is always at the center of the stick, even if the supports are not located the same distance from the center of the stick.

3) (True/False) If a third support was added somewhere between the two existing support strings, we could find the reactions of all three supports using only Statics.

This configuration is indicative of a common simply supported beam problem common to many Statics texts. An example is shown in Fig. 7.

E. Frames

The frames activity requires one tension protractor, one table clamp, one steel rod, a meter stick, a rod clamp, a small bolt, string, and masses of known value. The configuration is illustrated in Fig. 8.

Similar to examples recommended in the PASCO Scientific manual that accompanies the tension protractors, this activity encourages experiential learning activities focusing on correct FBD for pins and cables in systems with two-force and multi-force rigid members.

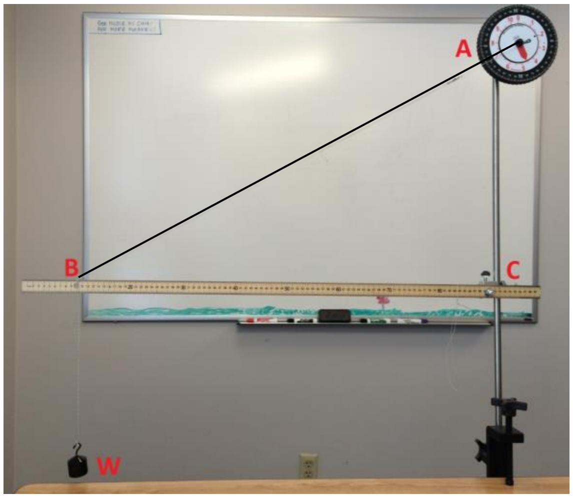

Fig. 8 Setup Frame Activity

For this activity, students are asked to record the tension and direction observed in the tension protractors, the location of each mass, and the value of each mass. Students pick the value of each mass to hang at one or more unique locations along the meter stick, but not to be located at B or C. Note that the meter stick is horizontal as determined by inspection.

The students are asked to calculate the force in the support string attached to the tension protractor given the angle of the string, the mass and center of mass of the meter stick, and the location and value of the suspended mass placed on the meter stick. If the calculated values match the measured values within 5%, the students have successfully solved the problem.

The follow-up concept questions include:

1) Assuming the weight of the meter stick is negligible, BC is a two-force member if the mass is applied at a) Point B or b) Any point in-between B and C.

2) If the angle of the string at B decreased (moved closer to being horizontal), the tension in the cable AB would _______(increase, decrease, stay the same).

A similar problem from Hibbeler's 14th Ed [7] is shown in Fig. 9.

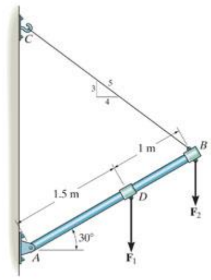

Fig. 9 Problem from Hibbeler's Statics14th Ed. [7] that is similar to the Frames activity.

G. Cables Subject to Concentrated Loads

The cables activity requires two tension protractors, two table clamps, two steel rods, string, and masses of known value to create the setup shown in Fig. 10.

The cables activity was developed by the authors to help students identify the FBDs that will lead to a solution when faced with many possible choices.

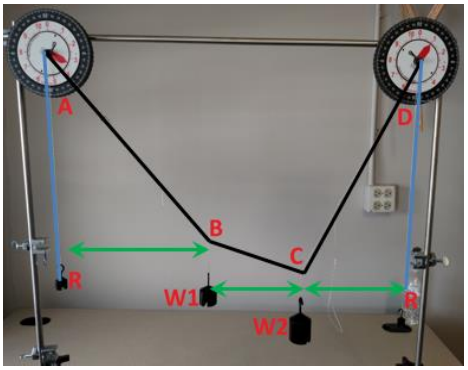

Fig. 10 Setup Cables Activity

For this activity, the students are asked to record the tension and angle of the forces at the tension protractors and the horizontal distances between points A, B, C, and D shown on Fig. 10. A small mass is suspended from each tension protractor that acts as a plumb bob so that students can easily measure the horizontal distances between A, B, C, and D. Students pick the value of each mass to hang at two unique locations given loops that have already been placed in the string.

The students are asked to calculate the force in segment CD using only the angle in segment CD, the horizontal distances, and the value of the suspended masses. Students must use the correct FBD in order that their calculated values match the measured values within 5%.

The follow-up concept questions include:

1) The maximum tension always occurs in which segment?
   A) The segment with the steepest slope,
   B) The segment with the flattest slope,
   C) It depends on the amount of weight at each point regardless of the slope of each segment.

2) Is it possible for the maximum tension to be in segment BC? Explain why or why not.

A similar problem from Hibbeler's 14th Ed. [7] is shown in Fig. 11 where the supports are at the same elevation, all horizontal distances are known, and the slope at one of the supports is known.

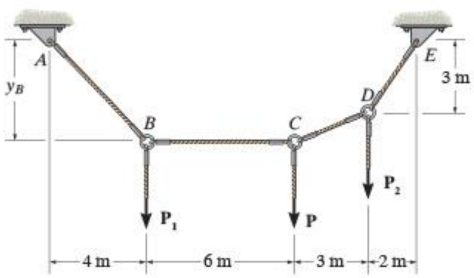

Fig. 11 Problem from Hibbeler's Statics14th Ed. [7] that is similar to the cables activity.

E. Friction

The friction activity was developed by the authors to help students conceptualize the relationship between the friction angle and the coefficient of friction and to identify when the force of friction is equal to the product of the coefficient of friction and the normal force on a contact surface.

The friction activity requires a medium density fiber board or other similar lumber product, masses, an inclinometer application on a smartphone, and a hardcover textbook to create the two instances of the setup shown in Fig 12.

Fig. 12 Setup Friction Activity

For this activity, the students are asked to record the friction angle by using the inclinometer application to determine the angle at which sliding occurs for two different scenarios shown in Fig. 12: 1) The mass on the hardcover book and 2) the hardcover book on the board. Students are asked to slowly increase the inclination angle until sliding occurs. Next, the students create the system shown in Fig. 13 and are asked to use the friction angles found in the previous step to determine whether sliding will occur first between the book and the mass or between the board and the book as the angle of inclination is slowly increased.

Fig. 13 Setup Cables Activity

Students then test their prediction and are asked the associated follow-up questions:

1) Would the object that slides first change if you used a different value of mass? Provide a one to two sentence explanation of your answer.

2) If the area of contact increases but the weights stay the same, would the friction force increase, decrease or stay the same?

3) Is the force of friction equal to the product of the coefficient of friction and the normal force between the surfaces when sliding did not occur? Provide a one to two sentence explanation of your answer.

A similar problem from Hibbeler's 14th Ed. [7] is shown in Fig. 14. The question asks for the angle which will cause sliding of one of the blocks given the coefficients of friction for block A and B and that the spring is unstretched.

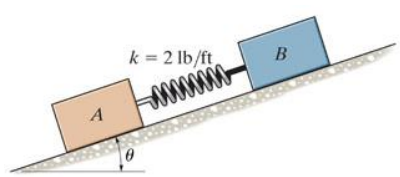

Fig. 14 Problem from Hibbeler's Statics14th Ed. that is similar to the Friction activity.

G. *Hydrostatic Fluid Pressure*

The fluid pressure activity was developed by the authors to help students grasp the relationship between the weight of water and pressure.

The fluid pressure activity requires a 19-liter bucket, a luggage scale, and a ruler or tape measure. For this activity, the students are asked to partially fill the bucket with water and determine the weight of the water in the bucket using the luggage scale. A water depth in the bucket of around 10 cm provides enough water for the activity. The students measure the volume of water in the bucket and then calculate the unit weight of water using the measured weight of water and the measured volume of water. Then, students are asked to calculate the hydrostatic pressure at the bottom of the bucket using the unit weight of water they calculated in the previous step. Next, students are asked to calculate the total hydrostatic force acting on the bottom of the bucket using the previously calculated hydrostatic pressure. The students should find that the hydrostatic force exerted on the bottom of the bucket is identical to the weight of the water in the bucket, thus solidifying the concept that fluid pressure is based on the weight of water. The follow-up questions further solidify their understanding and include:

1) What is the error between your measured value and the actual unit weight of water. The unit weight of fresh water is 9.8 kN/m^3. If the error is not less than about 5%, check your work or ask for help.
2) What is the error between the total hydrostatic force acting on the bottom of the bucket and the measured weight of water? These values should be essentially the same. Explain why this is the case.
3) If the bucket was full of water to the point that it was on the verge of spilling, how much would the water in the bucket weigh?

A similar problem from Hibbeler's 14th Ed. [7] is shown in Fig. 15. The question asks for the total hydrostatic force acting on the gate AB.

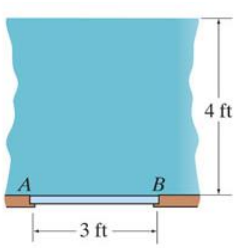

Fig. 15 Problem from Hibbeler's Statics14th Ed. [7] that is similar to the Hydrostatic Fluid Pressure activity.

III. Student Surveys

Student surveys were conducted to evaluate the effectiveness of the hands-on activities and help find opportunities for future improvement. The student surveys were completed during lecture using wireless data collection that allows for the anonymous collection of responses. The surveys were voluntary and were not part of the students grade for the course. Additionally, the students were not made aware of the survey in advance. The following two questions were posed to the students:

Q1) The hands-on activities help me understand the concepts in this course.
A) Agree
B) Neutral
C) Disagree
D) I haven't done a hands-on activity or I don't have an opinion

Q2) The hands-on activities helped improve my problem solving skills
A) Agree
B) Neutral
C) Disagree
D) I haven't done a hands-on activity or I don't have an opinion

Table I shows the percentage of responses for each choice for question 1 and 2 from Spring 2016, Fall 2016, and Spring 2017.

TABLE I
Student Survey Results

Question (Semester)	Answer Choice			
	A	B	C	D
Q1 (Spring '16)	35% (40%)[a]	38%, (36%)[a]	16% (14%)[a]	11% (10%)[a]
Q2 (Spring '16)	33% (34%)[a]	40% (40%)[a]	17% (16%)[a]	10% (10%)[a]
Q1 (Fall '16)	25%	39%	27%	8%
Q2 (Fall '16)	18%	44%	32%	6%
Q1 (Spring '17)	53%	32%	5%	10%
Q2 (Spring '17)	35%	46%	9%	10%

[a]Data was taken after the third exam, which typically occurs within the last month of the semester. All other data was collected after exam 1.

Note that in Spring 2016 data was collected after completion of Exam 1 and after Exam 3. Exam 1 occurred during the first four weeks of the semester after which the students only had opportunities to complete the first two hands-on activities: *2D Particle Equilibrium* and the *Pulleys* activity. Exam 3 occurred during the last four weeks of the semester which afforded students the opportunity to complete six of the eight activities. With the exception of the *Friction* and *Fluid Pressure* activity, all of the activates could have been completed by Exam 3 in Spring 2016. During the fall semester of 2016 and the spring semester of 2017, data was only collected after Exam 1 because little difference was found between the two surveys done in the spring of 2016. The respondents included approximately 200 in the spring semesters and 500 in the fall semester.

The content and execution of the activities has not been changed since the spring semester of 2016 and neither has the grading criteria. The grade breakdown of the course is such that four of the eight activities are worth approximately 1% of the total grade in the course and students have the opportunity to complete all eight activities if they elect. Any activities beyond the four required result in extra credit which can result in a maximum of approximately 1% bonus towards their overall grade. Overall, feedback seems to indicate that the students believe that the hands-on activities help them understand the concepts in the course and improving their problem-solving skills. The large increase in positive responses from 2016 to 2017 is unknown. It could be the cause of room locations and/or times when the activities are available for students or for a number of other reasons that are not relevant to this discussion.

IV. Conclusions

It is broadly accepted that hands-on exercises that display physical, measurable representations of mechanical realities are able to form connections between engineering predictions and the physical world in meaningful ways. More so, the connection, or sometimes re-connection, helps establish and reinforce the concepts that help form the basis of knowledge. The hands-on activities outlined in this paper represent physical demonstrations of classical Statics problems and help students experience, in a real tangible way, the effects of forces on systems at equilibrium. Most importantly because the students can easily measure the forces and angles that they subsequently calculate using the equations in Statics. Instructors alike benefit by having a means of communicating the subject manner in an effective way other than a traditional lecture format.

The effort to put mechanical demonstration models in front of students has received positive feedback from students and instructors alike. The models are fun and illustrative and require a minimum amount of time. Even though benefits seem obvious assessment results are ambivalent. But perhaps the focus of the assessment is not aimed properly. The effort outlined in this paper, as well as others, analyzes learning groups as a whole. It is possible that some groups, such as those predisposed to learning kinesthetically, may examine a more pronounced benefit. Subsequent studies should endeavor to identify learning groups as part of their assessment.

Similarly, the field lacks studies that analyze the rate at which concepts are internalized. It seems plausible that the depth at which concepts are learned is not dependent on the mode of learning, but students exploring the subject matter through hands-on models absorbed the concepts faster or with less effort than traditional book learners. The same may be true for the long-term retention of the subject matter.

A less speculative course for future endeavors might include the development of additional exercises focused on specific student interests or identifiable gaps in student comprehension of specific topics. Additionally, the hands-on activities lend themselves extremely well to science and engineering out-reach programs. The demonstrations have the ability to broaden the exposure of the engineering world to include audiences made up of various clubs, high school groups, or youth organizations. They are not lengthy to demonstrate, attract attention, and are a manageable travel size.

Acknowledgment

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