An Experiment in Hands-On Learning in Engineering Mechanics: Statics*

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Students in an introductory engineering mechanics (statics) course are randomly divided into two groups. Both groups receive identical instruction except for roughly once per week, for the first half of the semester. During these exceptional sessions, one group is given hands-on manipulatives with which to solidify concepts, while the other group is not. The degree of learning is assessed with a mid-term multiple choice concept test and mid-term problem solving whose questions have multiple interconnected parts. Overall, the two groups show no notable difference in learning. However, when one looks at electrical engineering (EE) students and mechanical engineering (ME) students separately, it appears that the EE students benefit from the hands-on exercises, while the ME students might be better without.

Keywords: engineering mechanics; statics; hands-on; inquiry learning

INTRODUCTION

ACCORDING TO CURRENT UNDER-STANDING, we humans think, learn, and solve problems by making connections and associations to our previous experiences [1]. It follows that if one's first exposure to engineering concepts takes place by passively hearing it in a lecture or by reading it in a textbook, the experience may not be sufficiently significant or rich to build connections.

Hake [2] conducted a study of more than 6500 students in 62 different introductory physics courses. He found that students taking interactive engagement (IE) courses had dramatically better conceptual understanding, than students taking traditional courses. Here, Hake defines 'interactive engagement' (IE) courses as:

> . . . those designed at least in part to promote conceptual understanding through interactive engagement of students in heads-on (always) and hands-on (usually) activities which yield immediate feedback through discussion with peers and/or instructors.

In Hake's study, 'traditional' courses are those that make little use of IE methods. A partial list of other studies that corroborate and build upon Hake's findings include [3–9]. Some of these other results are even more dramatic. One particularly interesting study is that by Redish *et al.* [10] who show evidence that the gains derived from IE learning are due to the type of instruction rather than differences in time on task or the skills of individual instructors. But how critical is the 'hands-on' component of interactive engagement? Later in the paper, we highlight multiple viewpoints expressed in the literature. Some researchers

see hands-on activities as particularly effective techniques for developing conceptual understanding. Others, favoring a more axiomatic approach, see experimentation as a less important activity for learning. Herein, we describe an experiment in which we randomly divided a large introductory mechanics course into two groups. One group was given objects that they can manipulate while they learn and explore mechanics concepts. The other group learned via interactive engagement, but did not have the hands-on manipulatives. In this paper, we present differences in learning between the two groups. Some subsets of students appear to benefit from the hands-on activities while others do not.

The research was conducted as part of the College Initiative on Teaching and Learning (CITL) within the College of Engineering & Engineering Technology at Northern Illinois University. Selected faculty members from all four departments in the college participated in a series of workshops where they completely redesigned courses they were teaching, posed educational research questions associated with the classes, and designed experiments to answer those questions.

MODELING IN ENGINEERING MECHANICS

Before describing the experiment and its results, it is instructive to characterize the nature of the engineering mechanics course that serves as our laboratory.

Like most mechanical engineering curricula throughout the country, we at Northern Illinois University (NIU) require undergraduates to take an introductory mechanics course from the physics

department. Shortly afterward, students must take a two course sequence in 'engineering mechanics' (statics and dynamics), taught by engineering faculty. The overlap between the physics course and the engineering courses is significant. Both the engineering and the physics courses cover vector arithmetic, Newton's laws of motion, impulse–momentum principles (linear and angular), and the work–energy principle. However, since these topics are so fundamental to mechanical engineering, many, if not most, of us find the overlap justifiable.

In the engineering mechanics courses, students often have to solve problems with multiple interconnected bodies. Typically, this makes the problems more difficult to solve, yet makes the problems more relevant to engineering. In our opinion, the most important contribution that the engineering mechanics courses make toward the undergraduates' education is the systematic engineering approach to modeling, analysis, and problem-solving that we try to inculcate into the students early in the curriculum. It is the same process that students will use later to study mechanics of materials, vibrations in mechanical systems, the dynamics of fluid systems, jet propulsion, and more.

To study the mechanics of machines and devices that engineers create, the engineer must first create a model of the object. In engineering mechanics, modeling is a process of abstraction in which real-world objects are represented by mathematical models amenable to rigorous analysis. Borrowing from Hestenes [11], we represent the two-step process schematically as shown in Fig. 1.

The lowest level in the figure represents the real world itself, containing all the machines and devices that engineers create. The first step in the modeling process that we teach is to create a free body diagram (FBD). The FBD is a graphical representation of the physical object, depicting all the forces and moments acting on it. In creating the FBD, one usually has to make assumptions or

approximations. For example, it is common to approximate real world objects as particles or as undeformable bodies. One might choose to ignore the weight of a component, or neglect friction. One may represent forces acting on a body as concentrated load applied to a single point. The forces that one draws on the FBD must always obey Newton's third law.

In the second step in the modeling process, we apply Newton's second law. Students translate the graphical model into a *mathematical* model. The set of equations that students derive express a relationship between known quantities given to them and unknown quantities that they wish to determine. This is 'Level 2' in Fig. 1.

Assuming that one is able to solve the equations in the mathematical model for the quantities of interest, one realizes the powerful analytical framework presented in Fig. 1. Solution of the equations which reside in Level 2, corresponds to the 'behavior' of the system depicted graphically in the FBD at Level 1. If the FBD is a good representation of the physical system, then the mathematical results shall closely predict the actual behavior (e.g. forces, accelerations) of the real-world system at Level 0. This process is a model for how even very complex engineering analysis works.

WHAT STUDENTS *DON'T* UNDERSTAND IN STATICS

Statics is the first of the two engineering mechanics courses we teach. In this course, none of the systems accelerate. Setting $a = 0$ in Newton's second law, converts the equations of motion in the form of ordinary differential equations (ODEs) into equilibrium equations in the form of algebraic equations. Often the algebraic equations are linear. As a consequence, they are relatively easy to solve. Thus when students have difficulties, the difficulties lie in creating an appropriate free body diagram or in deriving the equilibrium equations—levels 1 and 2 of Fig. 1.

The assertion is backed up by a recent paper by Streveler *et al.* [12]. They report initial findings of a Delphi study on engineering mechanics concepts that students find most difficult. The most difficult statics concepts on the list are: (1) static indeterminacy; (2) external vs. internal forces; (3) isolating a body from its surroundings; (4) couples; (5) static friction; (6) importance of signs on forces; (7) distributed forces; and (8) two force members.

According to the study, item 1 is the most difficult of the concepts in the list, while items 2 through 7 all tie for next most difficult. All these difficult concepts lie within the modeling phase of the problem solving process. (Although items 1 and 5 may also reside in the solution phase.) Interesting, but perhaps not surprising to those who teach statics, is that most of the difficult concepts are related to drawing appropriate free body diagrams.
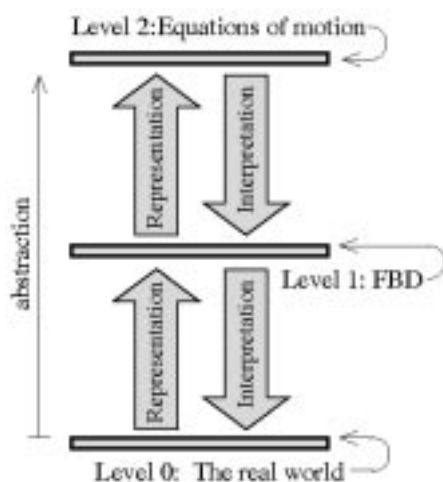

Fig. 1. Schematic depiction of the modeling process in engineering mechanics. Adapted from [11].

Also, it is worth noting that the difficult concepts are not natural concepts that the average person recognizes as he/she casually observes the physical world. To internalize the concepts, students must engage in deep thought, possibly supplemented by experimentation. Furthermore, students must recognize and abandon any misconceptions they have.

PERSPECTIVES ON INTERACTIVE ENGAGEMENT

Most engineering instruction is deductive. Theories and general principles are taught first; applications then follow. The practice appears to support a widely held misconception in engineering education practice that knowledge is something that can be simply transmitted from expert to novice.

Decades of research, however, supports an alternative model of learning (constructivism) in which knowledge is constructed rather than absorbed. Within this framework, knowledge is gained only after the new information filters through a student's mental structures that 'incorporate the student's prior knowledge, beliefs, preconceptions, misconceptions, prejudices, and fears.' [13] New information that is consistent with the existing mental structures is more likely to be integrated. Contradictory information, or information that simply does not connect with the existing mental structures, more often passes through without being absorbed into the knowledge base.

From this perspective, Prince and Felder [13] argue that engineering instruction should be inductive. Educators should start with applications that provide meaning and context to students, then we can build the theory on top of applications where the questions 'why?' and 'how?' can be answered readily. Prince and Felder define the term *inquiry learning* as instruction that uses questions and problems to provide context for learning, and that does not fall into related but more restrictive categories such as problem-based learning, project-based learning, case-based learning, discovery learning, and just-in-time teaching [13].

Instruction approach No. 1: Hands-on, heads-on
Laws *et al.* [3] provide a somewhat narrower working definition of inquiry-based learning in their studies of student learning in physics. Primary elements of their instructional approach are listed below:

1. Use peer instruction and collaborative work.
2. Use activity-based guided inquiry curricular materials.
3. Use a learning cycle beginning with predictions.
4. Emphasize conceptual understanding.
5. 5_1. Let the physical world be the authority.
6. Evaluate student understanding.

We call specific attention to item 5_1 of the list. In this instructional model, the instructor is not the authority. Neither is the textbook, nor the answers in the back of the textbook. Instead, students have access to a physical system that they can probe, test hypotheses, and verify understanding of particular questions they are asked. In this instruction model, students' small-scale experiments play a key role in concept acquisition.

Thacker *et al.* [9] and Steif and Dollár [14] espouse a similar approach. The latter authors argue that "physical experiences with the forces and moments that act between, or within, objects must be part and parcel of the very earliest exposure to statics." Similar in principle, Thornton and Sololoff [4] use digital simulations rather than physical manipulatives. Qualitative and/or quantitative data are provided by all these authors to support the efficacy of the instructional approach.

Instruction approach No. 2: Hands-off, heads-on
As an alternative to the hands-on approach described in the previous section, we also consider a second instruction model motivated by a perspective proffered by Hestenes [11]. He argues that the best way to teach mechanics, and physics in general, is to make a sharp distinction between the (real) 'Physical World' and the (conceptual) 'Newtonian World.' The Newtonian World (upper two levels of Fig. 1) is where mechanics/physics lives. It is defined by a set of axioms: the axioms of geometry and Newton's laws of motion.

At first glance, Hestenes's approach may appear rigidly deductive. The axioms or laws are presented upfront; then it is up to students to apply them to a litany of problems. However, Hestenes compares his approach to that of playing a game. Like chess, Hestenes's Newtonian modeling game has relatively few clearly defined rules that can lead to a rich set of outcomes. Unlike chess, the modeling game is not competition between players. Rather, it is more like a puzzle in which students are challenged to create representations of the physical world that are consistent with the Newtonian axioms. Students are encouraged to consider multiple representations, to test them, and to recognize patterns. In this instruction approach, students do not use experiments to acquire physical concepts. Instead, the role of experiments, if any, is to validate Newtonian models.

As Hestenes describes [11], the instruction approach is well aligned with the constructivist model of learning. In the current study, we couch a form of the Newtonian modeling game in an inquiry learning framework, as defined by Prince and Felder [13]. Specifically, we adopt the instructional approach outlined in the previous subsection, with one exception. In place of item 5_1, we substitute the following:

5_2. Let the axioms of mechanics be the authority.

In many ways this second instruction approach is similar to those found in typical textbooks, but

placed in an instructional setting that promotes interactive engagement.

RESEARCH QUESTION AND METHODS

Herein, we report on a research project in which we test the two modes of teaching just outlined. To keep the nomenclature simple, we will refer to these two instruction models as the 'hands-on' and 'hands-off' approaches. Specifically, we pose the following question:

> In an introductory engineering mechanics (statics) course, which teaching strategy is more effective on learning as reflected in mid-term and final examinations: hands-on or hands-off ?

In the following section, we provide a more detailed description of the hands-on and hands-off activities.

Before the first day of class, we randomly assigned students registered for the course into two groups. One group would periodically receive the hands-on instruction, while the other received hands-off instruction. Students who registered for the course late were assigned to a relatively small third group. Although the third group received 'hands-off' instruction, the performance of these students was not included in the statistics of the 'hands-off' group. Over the semester, a handful of students (distributed roughly evenly over all groups) withdrew from the course. Their data are not included in the analysis also.

In the first half of the semester, we periodically split the class. On these days, the two groups met in separate classrooms and received different instruction. The split occurred about once per week on average, usually coinciding with the introduction of new concepts. The class met three times per week. On other days, the entire class met in the same room. In the combined class sessions, we more often focused on problem-solving exercises similar to homework assignments in common textbooks.

The first few times we split the class, we also split the instructors. In other words, the teaching assistant and professor switched rooms half way through the class period. After a few attempts, we found this to be too disruptive to the flow of the class. For the remainder of the split sessions, the teaching assistant and professor alternated between groups on separate days.

During the split sessions, and also during many of the combined sessions, students worked in small groups of three or four students. The small groups were assigned at the beginning of the semester with the goal of achieving diversity in academic major, and number of years at the university. The majority of students were in the mechanical engineering program. A sizeable minority were electrical engineering students. Only a handful of students were in another major or were unaffiliated.
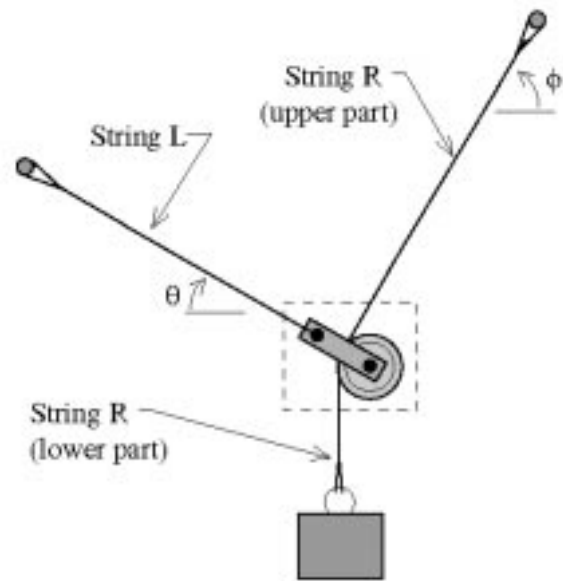
The periodic split sessions continued until we

Fig. 2. A pulley problem.

administered the mid-term exams. Afterward, both groups received common instruction. There was a hands-on project in which all students participated in designing and building trusses. In the second half of the course, the instructor, rather than the students, performed in-class demonstrations.

STUDENT ACTIVITIES

The differences between the two teaching approaches are best illustrated by describing the specific activities in which the students engaged.

A pulley problem

At the end of the first week of class, we ask students to analyze the system shown in Fig. 2.

Both groups of students are asked to examine how the tensions in String L (T_L), the upper part of String R (T_{RU}), and the lower part of String R (T_{RL}) change as one varies the angle ϕ. The investigation should be described as a preliminary study, aimed at getting students engaged in a problem before the standard textbook analysis is performed in class. Specifically, at the time students receive the assignment, we had covered the meaning of 'Force,' and that all the forces must exactly balance for the system to be in equilibrium. Furthermore, we had completed an in-class exercise in which students studied the nature of tension in a straight rope without a pulley. Students found that tension is essentially constant along the length of a light-weight string. Tension varies linearly along heavy, hanging chains. At the time of the assignment, we had *not* covered the usual approach of solving this problem by decomposing the vectors into components, and then formulating and solving equilibrium equations.
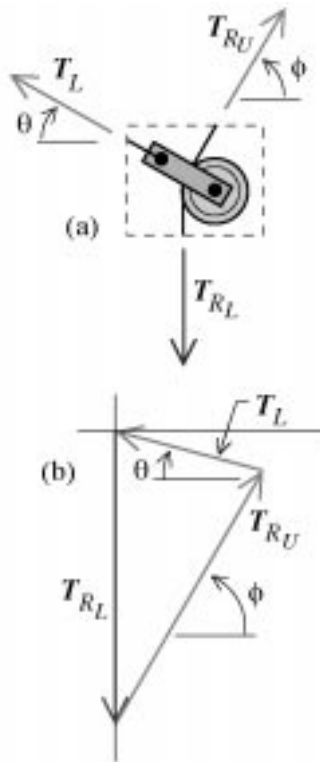
Fig. 3. Vector addition of external forces, demonstrating equilibrium.

Both groups begin the exercise by hypothesizing. Students sketch plots of T_L, T_{RU}, T_{RL}, and θ, separately, as functions of ϕ. Next, they explore. We give students in the 'hands-on' group string, springs (for measuring tension), a pulley, protractor, ruler, and block to carry out the physical experiment. Plotting the tensions and angle θ as functions of ϕ, students observe trends. Specifically, they *discover* that T_{RU} does not change with ϕ; it is always equal to the weight of the block.

The 'hands-off' group does not get hardware to manipulate. Instead they are asked to consider the forces acting on the pulley (assuming one can neglect the weight of the pulley). Students are asked to depict the three forces on the pulley graphically as indicated Fig. 3(a).

Magnitudes and directions of the forces are represented by lengths and directions of the arrows. In order for the pulley to remain in equilibrium, all the forces must balance out. Therefore, when arranged head-to-tail the three arrows close to form a triangle. Students were told to *assume* that the tensions in the upper and lower parts of String R are identical: $T_{RU} = T_{RL}$. (Since this exercise occurs before discussion of moments, we do not derive the result from first principles.) Armed with a ruler, protractor, pencil, and paper they are able to draw the force triangles (Fig. 3(b)) and discover how the system responds to changing ϕ.

Before returning to the next meeting of the course, students in both groups had to use their findings to compare and evaluate competing designs for a box-hoisting system.

To summarize, we asked both groups of students to solve the exact same problem. The 'hands-on' group did it purely through experimental means. In doing so, they discovered that tension in a cord does not change as it passes through a pulley. In contrast, the 'hands-off' group solved the problem by exploring, graphically, what it means for forces to balance out and achieve equilibrium. To do so they were told to assume the tension remains constant through the pulley.

Geometry of vector decomposition

In the next split-class exercise, students were asked to consider a 200-lb person standing on a scale. When the scale lies flat on the floor, it reads 200 lb. What does the scale read when it lies on an inclined surface? Students are asked to find the scale reading (i.e. normal force) as an explicit function of ϕ. This is an exercise taken from the Website www.handsonmechanics.com.

Again, we ask students to form a hypothesis based on hand-sketched free-body diagrams and/or intuition. Then they get to work. At the time of the assignment, students had experience with the standard process of solving two-dimensional particle equilibrium problems: drawing a free body diagram, decomposing forces into horizontal/vertical components, and then formulating/solving the equilibrium equations. We monitored students' progress closely. As expected, almost all groups encountered difficulty in figuring out (on the fly) the trigonometric manipulations necessary to express the normal force as a function of ϕ. As an alternative approach, we urged the groups to decompose the forces into components parallel and perpendicular to the inclined surface. Upon doing this, the normal force separates out much more cleanly. But did they get the answer correct?

Throughout the process, students in the 'hands-on' group had access to a bathroom scale, a board, and blocks with which to create the incline (Fig. 4). They were encouraged to use it to check their intuition, and to check qualitative agreement with the final answer generated from analysis.
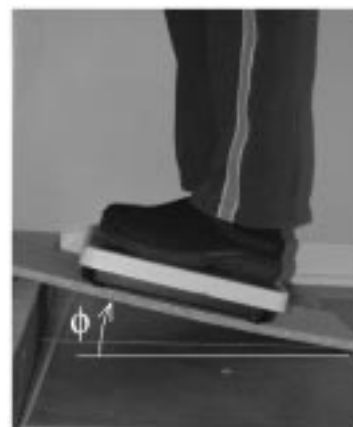
The 'hands-off' group, which did not receive

Fig. 4. Bathroom scale used in a vector decomposition activity.

equipment to test their answers, was encouraged to play Hestenes' Newtonian games. In the students' analyses, they made no assumption on the magnitude of ϕ. Therefore the solution should be valid (consistent with the assumptions) if ϕ takes on extreme values such as 90°, 0°, and –90°. Students performed these mental exercises, interpreted the results, and then evaluated their validity.

Exploring moments

About a week later, after introducing students to moments, students were asked to consider a set of problems regarding the 'F'-shaped body shown at the top of Fig. 5. The body lies in a horizontal plane and is pinned so that it is free to rotate about point A. We asked the students nine questions, three of which are shown in the bottom half of Fig. 5. Under the loading conditions shown, students are told that the system is in equilibrium. Then they are asked which of the following are true: (A.) $0 < |F_1| < |F_2|$; (B.) $0 < |F_2| < |F_1|$; (C.) $0 < |F_1| = |F_2|$; or (D.) either $|F_1|$ or $|F_2|$ *must* be zero. Furthermore, students were asked to provide a one or two sentence justification for their choice. Justification typically involved identifying appropriate moment arms and then making proper comparisons.

Students in the 'hands-on' group received physical representations of the 'F'-shaped bodies as depicted in the bottom right corner of Fig. 5. They can apply the forces by attaching springs to the body and pulling. One can *feel* which force is bigger and see which is bigger by observing the relative lengths of the stretched springs. However, students were required to give a more rigorous justification for their answer than simply saying that one force 'feels' larger.
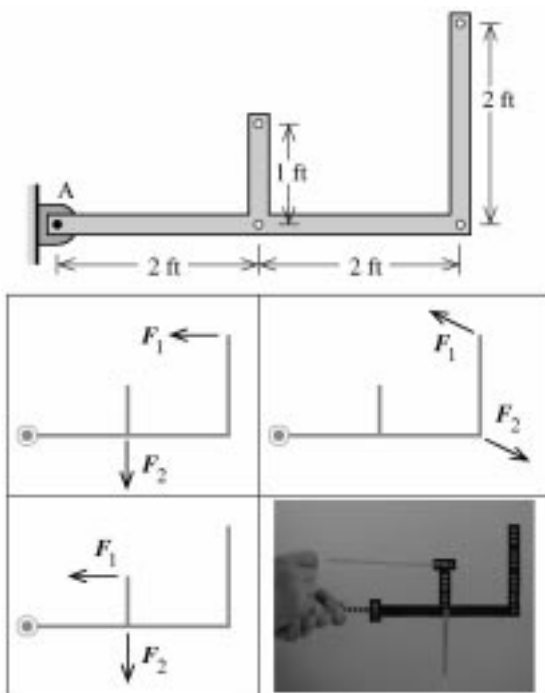
Again, the 'hands-off' group does not get to use the manipulatives. Instead, they must solve the problems by intelligent decomposition of position and force vectors and by the principle of transmissibility. Students in the 'hands-off' group are encouraged to find multiple justifications. The rules of the Newtonian Game, students are told, are self consistent; different (valid) approaches should lead to the same result.

Tipping criterion for a crane

Consider the crane shown in Fig. 6. At some point in the course, students become relatively proficient at performing straightforward force calculations. For a given crane load, for example, one can calculate the support forces that the ground exerts on the tracks of the crane.

One can exercise students' higher order thinking skills, by rephrasing the problem. For example, we asked students to calculate the minimum load that will cause the crane to tip over. Novices are often confounded by such problems. They often attempt to incorporate the dynamics of the crane tipping into their formulation. Of course, the proper approach is to formulate it as a statics problem, and then calculate the load for which the assumption of it being a statics problem is on the verge of being violated. In this problem, the violation occurs when the normal force on the crane's track at A becomes zero.

When solving the problem, students in the 'hands-on' group get a toy crane made from Lego™ to play with. If or when students got stuck, the instructor guided them through a

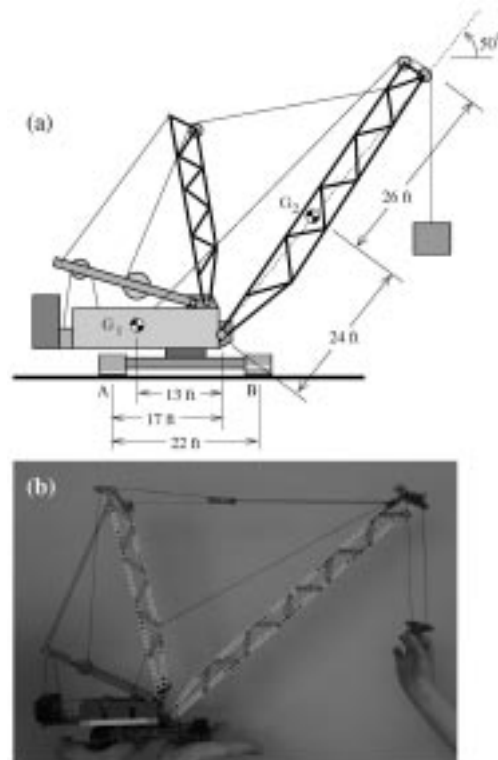Fig. 5. 'F'-shaped body for studying moments.

Fig. 6. Tipping crane activity.

simple hands-on experiment. One student lets the crane rest in his or her hands as shown in Fig. 6(b). One track rests in the student's right hand, while the other track rests in the left. Without any load, the crane's weight is distributed roughly evenly between the two hands. When another student pulls down on the hook, slowly increasing the load, the student holding the crane *feels* the force on one hand increase while the force on the other hand decreases. The student observes that the normal force vanishes as one of the tracks lifts off his or her hand, and the crane begins to tip. It becomes clear how to express the tipping criterion mathematically.

Students in the 'hands-off' group do not get cranes. When they run into trouble, the instructor guides small groups of students through a similar thought experiment in which they examine the solution of the static equilibrium equations as the load is slowly increased. Rather than feel the tipping criterion tactilely, the 'hands-off' students observe it within the mathematics, where one of the assumptions in their model is violated.

Design of a crane boom

In another in-class/split-session activity, we asked students to evaluate four crane designs, two of which are shown in Fig. 7. For the two cranes shown in the figure, one has a secondary boom, while the other does not. To figure out the purpose that the secondary boom serves, students are asked to investigate cable tensions in the two configurations. Not enough information is given to calculate tensions explicitly. Yet there is enough information to determine relative magnitudes.
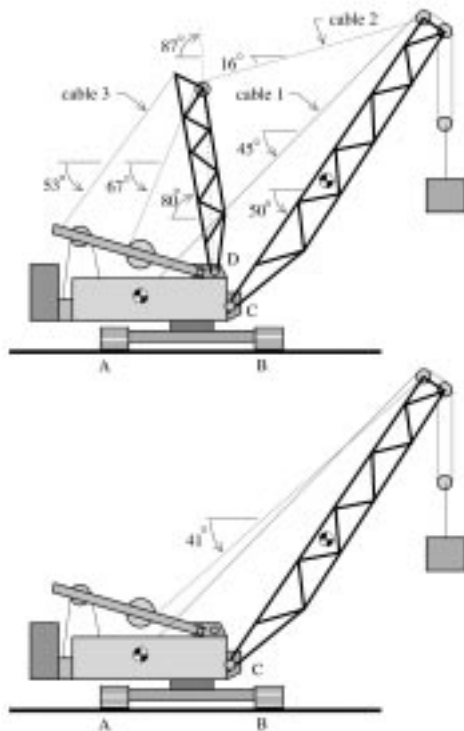
Students are required to justify their answers based on the geometry of the problem and conditions for static equilibrium. Therefore, both groups of students needed to employ a 'heads-on' approach. Students in the 'hands-on' group, though, were able to manipulate a toy crane while formulating their answer.

A friction problem

One of the teaching objectives of the course is to introduce students to the static Coulomb friction model. In a lecture period following an introduction to static friction, students were asked to consider the cart-like device depicted in Fig. 8 resting on an inclined plane. The cart has one set of wheels that are free to rotate, and a skid which provides friction to keep the cart in place. Students are to consider the cart in two configurations (Figs. 8(a) and 8(b)). In one, the cart is oriented so that the skid is downhill of the wheels. In the other configuration, the skid is uphill. Students were asked to find the maximum angle ϕ in Fig. 8 for which the cart will remain stationary on the surface. Many novices believe that the angle should be the same in both cases. After all, it is the same cart.

Again, it is a standard statics problem, except for the fact that there are no specific lengths or numbers given. Students are guided to draw free body diagrams, and formulate conditions for equilibrium, defining variables as they see fit. The new element in the problem is the Coulomb model for static friction. Students must recognize that the friction provides whatever force is necessary to maintain static equilibrium, as long as that force

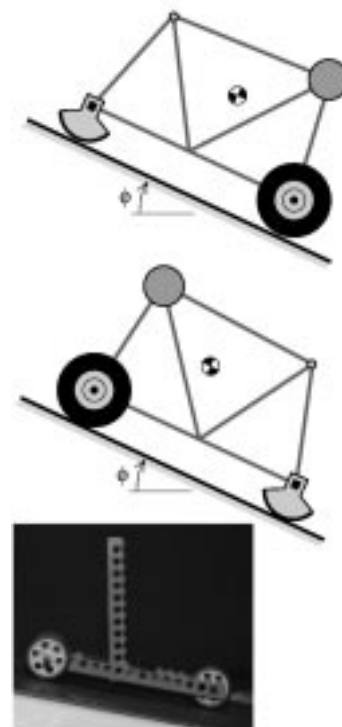Fig. 7. Different crane designs for students to evaluate.

Fig. 8. A static friction problem.

is less than a threshold proportional to the normal force. Students are to work through this process and use the line of reasoning to argue which configuration is more prone to sliding down the slope.

Students in the 'hands-on' group are given a toy cart made from Lego^{TM} and ancillary equipment to tinker with as a guide in their analysis. The 'hands-off' group does not get the carts. They are given extra encouragement to consider how the situation changes as one varies parameters such as the wheel base and static friction coefficient. They are encouraged to consider special situations such as $\mu = 0$ and $\phi = 0$ and question whether the results make sense.

Static indeterminacy

In one of the split sessions, we ask students to find the three string tensions in the planar problem shown in Fig. 9(a). It looks similar to a problem we studied at the beginning of the semester, and they dove in. The students were able to derive two equations which reflect horizontal and vertical force balances. However, they were unable to generate a third independent equation by taking a moment about any point. Thus, they are unable to solve for the three unknowns.

The problem is an example of static indeterminacy, and it is confusing to students. It seems like a well-posed problem for which one should be able to calculate tensions. However, it has no solution.

We give students in the 'hands-on' group materials with which they can create the three-string planar system. They quickly *discover* that it is not easy to create. If string 2 is a couple of millimeters too short, then string 3 goes slack (Fig. 9(b)). Likewise, if string 3 is a couple millimeters too short, string 2 goes slack (Fig. 9(c)). Therefore, it is not a well-posed problem. The problem becomes well-posed, however, when one replaces one or more of the strings by springs that stretch. Then,
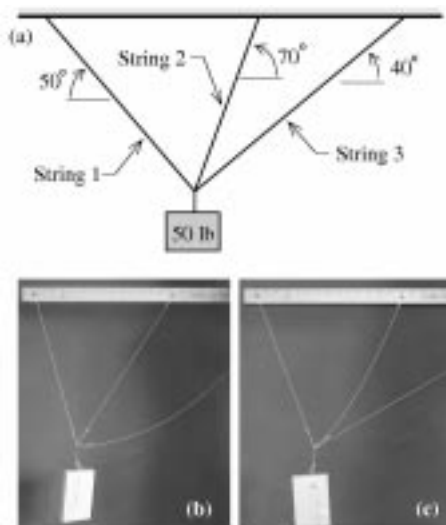
the tensions depend on the relative stiffnesses of the springs.

To help the 'hands-off' students wrap their heads around the conundrum, we guided them through a thought experiment. It is clear that string 3 is not necessary for equilibrium when string 2 is in place, and vice versa. Therefore, we asked what happens when we replace one of these strings by a wet spaghetti noodle. Clearly the noodle cannot support more than a minute fraction of the 10-lb weight. The answer to the problem depends on properties of the 'strings.' It is a problem beyond the scope of statics analysis.

Two-force bodies

In another activity, we ask students to find the support force at pin A for the system shown in Fig. 10(a). The activity occurred a little more than a week before we began talking about trusses and frames in earnest. To solve the problem, we told students to begin by drawing a free body diagram of the part AC.

After drawing a FBD similar to that shown in Fig. 10(b), students become stumped. There are four unknowns in the pin forces at A and B. Yet, there are only three independent equations one can derive. It looks like a statically indeterminate system. Nonetheless, students are asked to take a closer look at part DB.

Those in the 'hands-on' group get long slender rods like those shown in Fig. 10(c). Students are able to grasp the rod at two pin joints. By handling and manipulating the rods, they discover that
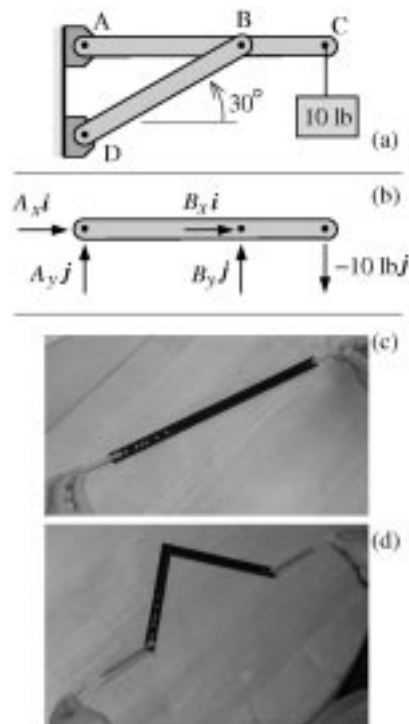

Fig. 10. A problem illustrating the characteristics of a two-force body.

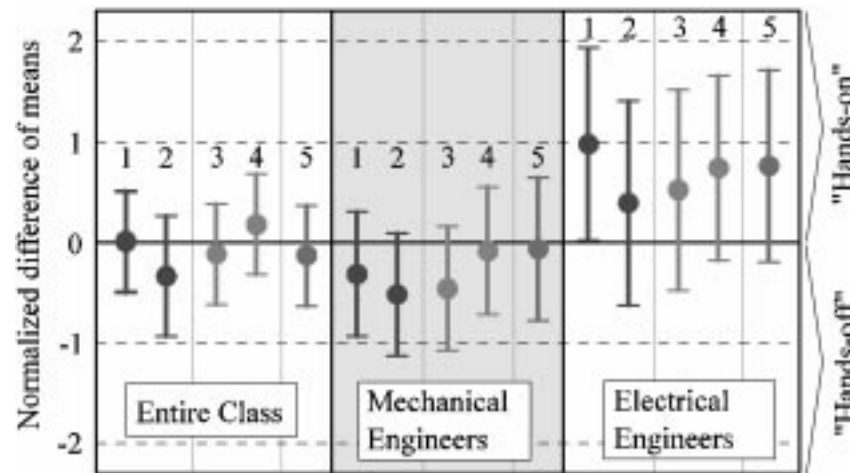Fig. 9. A statically indeterminate problem.

Fig. 11. Five measures of student learning for the entire class, just the mechanical engineering students, and just the electrical engineering students. Scores are normalized according to Equation (1). The learning measures are: (1) mid-term concept test; (2) mid-term problem-solving test; (3) final concept test; (4) final problem-solving test; and (5) the Statics Concept Inventory.

forces acting on the two-force body must be collinear.

Students in the hands-off group are guided toward this result in the traditional axiomatic way: by drawing a free body diagram and setting up equilibrium conditions.

Armed with is the colinearity, result students in both groups are able to eliminate one of the unknowns in the problem and solve for the reaction forces. Finally, we discuss odd-shaped two-force bodies such as that shown in Fig. 10(d).

Summary of activities

In each of the activities described above, both the 'hands-on' and 'hands-off' groups were given the same question to answer. Except for the first pulley exercise, both groups were asked to provide rigorous justification based upon statics principles. In this sense, we say that both groups are 'heads-on.' The primary difference lies in whether or not the group receives an artifact that students can manipulate while working through the details of the problem. Those in the 'hands-off' group who are not given the manipulatives, are often encouraged think about the limits of their solutions and to solve the problems in multiple ways. In this regard, perhaps, one can consider the 'hands-off' group to be a little more 'heads-on.'

RESULTS

To test the effectiveness of the teaching approaches, we collected five measures of student learning. The first two occurred near the half-way point in the semester when we administered two mid-term exams. The first exam was a multiple choice concept test for which questions can be answered without numerical calculations. Some of the questions were similar to Stief's [15] concept inventory questions in which students had to select which combination of arrows is a correct repre-

sentation of forces in part of a free body diagram. Other concept test questions were similar in nature to the questions in Fig. 5 for which students had to determine which of the forces acting on a body in equilibrium are largest. Other problems were similar to that suggested by Fig. 4 in which a system is shown in two or more slightly different configurations. Students had to determine the relative magnitudes of support forces in each of the configurations. Questions on the concept test often involved multiple principles. Students took the concept test on a Friday. Immediately after the exam, solutions were posted online so that students could receive feedback on which concepts were not clear.

On the following Monday, students took a problem-solving test consisting of two traditional mechanics exercises similar to the multi-part homework problems that one finds in textbooks. On the problem-solving test, students were asked to demonstrate that they are able to complete the entire problem-solving process from drawing correct free body diagrams; resolving forces into appropriate components; constructing equilibrium equations; solving the equations; and making a correct interpretation of the result. To grade the problems, we used a rubric that assigns points to each step of the process. It is the same rubric used to grade homework problems. Therefore, going into the exam, students knew exactly what was expected of them.

We conducted the final exam similarly. Students took a multiple choice concept test during the second to last lecture period of the semester. Solutions were posted immediately afterward. Then, five days later, students took a problem-solving test to complete the course.

The fifth assessment of learning was the Statics Concept Inventory developed by Steif [15]. It was administered online over the Internet during the week preceding the final concept test. Students were not required to take the Statics Concept

Inventory, and their score was not included in their final grade. To motivate students to take the inventory and to take it seriously, we told students that it would be good practice for their final concept test.

According to Steif [16], the correlations between students' exam scores and scores on several categories of the concept inventory are among the highest of all schools participating in the concept inventory. This provides some degree of validation to the assessments reported here.

In Fig. 11, we report the overall results of the five measures of learning. We are particularly interested in the differences between the 'hands-on' and 'hands-off' groups. Therefore, in the figure, we present a normalized difference between the average scores:

$$\frac{\bar{X}_{on} - \bar{X}_{off}}{S} \qquad (1)$$

Here, $\bar{X}_{on}$ and $\bar{X}_{off}$ are the sample averages of scores from 'hands-on' and 'hands-off' groups. Also, S is the standard deviation of the relevant sample. Specifically, when we compare the hands-on and hands-off groups of the entire class, S is the standard deviation for the entire class. However, when we compare the two groups within the subset of mechanical engineering students or electrical engineering students, we use the standard deviation of these subsets. The error bars represent the 95% confidence intervals of the difference for each of the measures, as defined by the corresponding t-distributions. The error bars are symmetric, so each truncated tail represents 2.5% probability.

Consideration of the class as a whole

Figure 11 shows that when one looks at the class as a whole, there is little if any discernible difference between the hands-on and hands-off groups. Upon performing standard two-tailed t-tests for difference of means, we obtain $p = 0.942, 0.176,$ 0.616, 0.503, and 0.469 for the five measures respectively. At first glance, it is difficult to say that either group performed better as a consequence of their particular learning experiences.

Consideration of mechanical and electrical engineering students separately

The picture becomes potentially more interesting, however, when we consider mechanical engineering students and electrical engineering students separately. On average, mechanical engineering students in the 'hands-off' group performed better than their counterparts in the 'hands-on' group in all five measures. However, we cannot assert with 95% confidence that the difference is statistically significant since the two-tailed t-tests yield $p = 0.307, 0.086, 0.136, 0.777, 0.845$. The midterm problem solving exam is the closest to meeting our criterion for significance.

When we consider the performance of electrical engineering students, we do see a statistically significant difference in the midterm concept test. On average, electrical engineering students in the 'hands-on' group performed almost one standard deviation better on the midterm concept test than their counterparts in the 'hands-off' group. The two-tailed t-test on this statistic yields $p = 0.037$, indicating statistical significance. Electrical engineering students in the 'hands-on' group performed better on the four other learning measures as well. The average differences were as large or larger than all other average differences observed. However, the error bars for the electrical engineering students were particularly large due to the relatively few electrical engineering students in the course. There were 18 electrical engineering students (8 hands-on, 10 hands-off) compared to 65 students (31 hands-on, 34 hands-off) overall. Had the sample size been larger, the differences in the other measures may have been statistically significant as well.
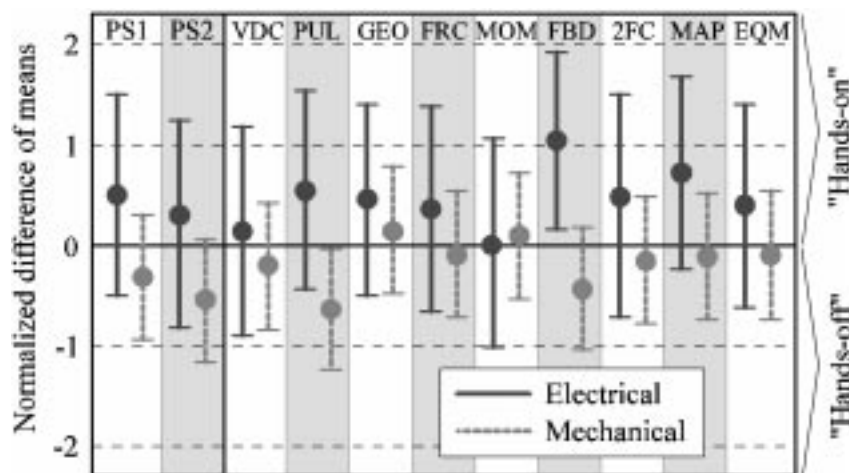

Fig. 12. Categorical details of the mid-term problem-solving and concept tests. Two sets of data are shown: one for electrical engineering students (solid error bars) and the other for electrical engineering students (dashed error bars) in the course. Scores are normalized by Equation (1). Specific categories are outlined in the text.

General test details

Since splitting the class into two groups only persisted for the first half of the semester, the most likely place to see the different effects of the teaching strategies is in the mid-term exams. This is corroborated, at least in part, by the summary data in Fig. 11. In Fig. 12, we present more details of the two mid-term exams. Data in Fig. 12 come in pairs, showing how mechanical and electrical engineering students separately performed in each of the categories. As before, the data indicate a difference in average performance between the 'hands-on' and 'hands-off' groups, normalized by the standard deviation (Equation (1)).

The first two pairs labeled 'PS1' and 'PS2' indicate difference in performance on the two questions on the mid-term problem-solving exam. The first problem (PS1) is similar in content to the bathroom scale problem discussed previously. By choosing to decompose the forces acting on an object into directions tangent and perpendicular to a cable, the equations of static equilibrium become especially easy to solve. Otherwise it takes a bit more work. Problem (PS2) is one for which students need to determine the conditions under which an object is on the verge of tipping, similar to the crane discussed previously.

The remaining nine pairs of data are categories in the midterm concept test.

- Category VDC. This is a series of straightforward vector decomposition problems in which students were asked to express vectors into mutually perpendicular but nontrivial basis vectors.
- Category PUL. This is a set of pulley problems in which students had to recognize that tension on the two sides of a cord laced through a frictionless pulley are equal.
- Category GEO. Problems within this category test whether students can recognize, based on the geometry of the problem, whether some forces are larger than other forces. The bathroom scale problem discussed previously is an example of such a problem.
- Category FRC. This is a sequence of problems that test students' understanding and misconceptions about the standard Coulomb model of static friction.
- Category MOM. This is a set of straightforward but nontrivial problems similar to those described previously which assess students' ability to calculate and evaluate relative magnitudes of moments.
- Category FBD. This is a series of problems that test whether students are able to select correct free body diagrams of systems with pins, slots, rollers, and systems with negligible friction.
- Category 2FC. Problems that test whether students are able to recognize when bodies are two-force bodies and select a free body diagram that properly reflects the configuration.
- Category MAP. This is a set of moment application problems. To receive points in this category, students must recognize the relative magnitudes of moments and determine whether, as a consequence, certain forces are larger than other forces.
- Category EQM. A set of squares are shown with forces acting on them. Students are asked whether it is possible for the squares to be in equilibrium.

As before, the data in Fig. 12 express the difference between average scores in each of the categories, normalized by standard deviation of the corresponding subgroup as expressed in Equation (1).

Many of the problems in the mid-term concept test do not fit uniquely into the categories listed in Fig. 12. The two-force problems (2FC) problems, for example, fit naturally as a subset free body diagram (FBD) problems. Therefore, for some problems, a correct answer would yield credit in two categories presented in Fig. 12. (In calculating students' grades, they did not get multiple credit.) Because we have problems that span multiple categories, interpretation is not as clean as one would prefer in a research project.

Details for electrical engineering students

In the free body diagram (FBD) category, we see that EE students in the 'hands-on' group score significantly higher ($p = 0.022$, two-tailed) than their counterparts in the 'hands-off' group in the FBD (free body diagram) category. As noted in our discussion of what student do not understand, this is one of the most important concepts for students to learn.

Because there are relatively few EE students, error bars on the electrical engineering score differences are quite large. The difference between the 'hands-on' and 'hands-off' EE students needs to be on the order of one standard deviation in order to reject the null hypothesis that the means are the same (95% confidence, two-tailed). In the FBD category, the difference between the averages is 1.04 standard deviations.

None of the other categorical differences reaches that large threshold. Nonetheless, electrical engineering students in the 'hands-on' group consistently scored higher than those in the 'hands-off' group in all the other eight categories. This consistent difference in favor of the 'hands-on' group accumulates to produce a statistically significant different difference for the concept test as a whole. Recall Fig. 11.

Details for mechanical engineering students

Although less dramatic, the story for mechanical engineering students is almost exactly the opposite. Our ME students in the 'hands-on' group scored lower than students in the 'hands-off' group in almost all categories. The category of pulley problems (PUL) is the only one that reached the threshold of statistical significance ($p = 0.039$).

Interestingly, the categories (PUL, FBD, 2FC, MAP) for which our difference measure is most negative for mechanical engineering students are the same categories for which the measure is most positive for electrical engineering students. A similar reflection property also exists for the mid-term problem-solving exam problems.

Differences between electrical and mechanical engineering students

In closing the results section, it is worth noting that we found no statistically significant difference between the ME and EE students on their four mid-term and final exams. The EE students outperformed their ME counterparts on the mid-term problem-solving test and final concept test by margins of 0.04 and 0.10 standard deviations respectively ($p = 0.91$, and $p = 0.70$). The ME students outperformed the EE students on the mid-term concept test and final problem-solving test by margins of 0.28 and 0.27 standard deviations respectively ($p = 0.33$, and $p = 0.36$). When one breaks the exams into categories similar to that shown in Fig. 12, the only significant difference found was in friction problems (FRC), in which the ME students scored better.

RECAP AND DISCUSSION

The statement seems obvious: students will learn mechanics concepts better when they have the opportunity to simultaneously see and feel the phenomena through direct hands-on experiments. The study described herein, however, suggest that the statement is not necessarily true. On the whole, we found essentially no difference between students who were given hands-on manipulatives and those who were not. Both groups of students received instruction that was largely inquiry-based and inductive.

Upon closer inspection of the data, however, there appears to be more subtle differences in how mechanical engineering students and electrical engineering students respond to the two teaching approaches. Specifically, we found that EE students in the 'hands-on' group performed better on a mid-term concept test than their counterparts in the 'hands-off' group. The difference is statistically significant in our experiment.

Mechanical engineering students appeared, in some sense, to respond in the opposite way. Those who were given the hands-on manipulatives, on average, performed worse. In fact, they performed worse on all measured categories in the two mid-term exams. Nonetheless, the differences were not large enough for us to rule out definitively the possibility that the result might be due to random chance.

We find the different responses among the EE and ME students rather curious and unexpected. It is a result that might lead one to suspect that there are other factors in play. Rather than consume considerable space describing details of non illuminating data, we simply mention that we did not find any significant differences among the groups and subgroups in their learning styles as measured by Felder and Silverman's [17] *Index of Learning Styles*. Furthermore, there was no significant difference in students' mechanical reasoning ability at the beginning of the semester as measured by the *Differential Aptitude Test for Personal Career Assessment*. The mechanical reasoning test measures the ability to 'understand basic mechanical principles of machinery tools and motion.' 'Items represent simple principles that involve reasoning rather than specialized knowledge or training.' [18] The test is designed for people with no more than a high school degree.

Therefore, the different response of ME and EE students to 'hands-on' and 'hands-off' instruction that we observed here remains a mystery. Anecdotally, both the primary instructor and the teaching assistant observed that students in the 'hands-on' group might have been having too much fun. 'Playing' with the Lego™ may have been a distraction from the learning objectives of the hands-on activities. Since electrical engineering students, almost by definition, are not as inclined to be as interested in mechanical gadgets, perhaps they were better able to focus on the learning tasks and benefit from them. An anonymous reviewer of this article suggests that the EE students, who have less experience with mechanical systems, may have been differentially motivated by the hands-on experiences. In any case, we do not have data to support or refute these speculative conjectures.

Before concluding, we should emphasize that the degree to which one can generalize our findings to other examples of 'hands-on' versus 'hands-off' instruction is unclear. Certainly, the hands-on exercises could have been designed better. If we had been aware of Dollár and Steif's work on creating hands-on modules for statics [19], including the way in which they re-organized the class, at the time we began the project, we likely would have designed our hands-on activities differently.

Given this, we hope the present work provokes broader and deeper study into the impacts that hands-on manipulatives can have on learning, and how the impacts vary in different parts of the student population.

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