AC 2011-1121: ASSESSING FIRST-YEAR PHYSICS MECHANICS KNOWLEDGE AND SKILLS NEEDED FOR A SOPHOMORE STATICS AND DYNAMICS COURSE

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Assessing First-year Physics Mechanics Knowledge and Skills needed for a Sophomore Statics and Dynamics Course

Abstract

Anecdotally, engineering faculty members complain that students taking sophomore engineering science courses are not prepared with respect to mechanics-based physics. However, evidence has rarely been systematically collected and analyzed to determine the veracity of these assertions. Therefore, the paper intends to address two questions:

- With respect to a knowledge of first-year physics mechanics, what do engineering faculty members expect students to know and be able to do when they begin a sophomore statics and dynamics course?
- To what extent do students satisfy these expectations?

To begin to address these questions, the following steps were taken. First, engineering faculty members who taught a sophomore statics and dynamics course at a large public university were asked for problems involving first-year physics mechanics that they thought students should be able to solve when they entered this course. For each problem, one or more learning outcomes were abstracted. Given the set of learning outcomes engineering faculty members expected students to be able to perform, a set of 17 problems was generated to be given to students near the beginning of the statics and dynamics course. The instrument has been administered to a set of students who took the course summer 2010 as well as a set of students who took the course in fall 2010. The paper will describe:

- Some of the problems that were submitted by engineering faculty members
- The set of learning outcomes that was generated
- The pre-course assessment instrument for physics knowledge and skills that was generated, and
- Results from over 350 students who took the pre-test.

After administering the instrument and analyzing the results, faculty members have a better idea of the background of their students and can adjust course content. Further, there will be evidence to examine the extent to which students are prepared in physics mechanics to begin a core engineering science course. Finally, the paper will also present changes that some faculty members made in the course plans to apply what they learned about the extent of their students' preparation in physics near the beginning of the course.

Introduction

Engineering faculty members have long assumed that student knowledge and skill with respect to physics is a major part of the foundation for their progress in studying many engineering disciplines, including mechanical engineering. ABET Engineering Criteria require that at least twenty-five percent of the credits for an engineering program be taken in mathematics and science courses, and some of the science courses for mechanical engineering curricula are expected to be in physics[1]. While importance of physics for success in studying mechanical (and related) engineering disciplines is unquestioned, deeper understanding of both how mechanical

engineering faculty members expect their students to apply physics and the extent to which mechanical engineering students are prepared to satisfy the expectations of their faculty members is required. Therefore, the paper intends to address two questions:

- With respect to knowledge of physics mechanics and skill in applying this knowledge, what do engineering faculty members expect students to know and be able to do when they begin a sophomore statics and dynamics course?
- To what extent do students satisfy these expectations?

Background

At least as far back as the 1960s, researchers began to discover that learners offered explanations for physical phenomena that were at odds with common scientific understanding[2]. For example, researchers found that many learners thought that forces needed to be exerted on bodies so that they would continue to move at constant, non-zero velocities. Perhaps the most intriguing result of this research was that learners retained their belief in the alternative explanations, even after instruction. Today, a multi-disciplinary research field studies conceptual understanding of learners, including what is conceptual understanding, how conceptual understanding can be assessed, what are common alternative explanations that learners offer for physical phenomena, and how learners can be influenced so that their explanations reflect common scientific understanding[3]. Duit maintains an active bibliography for this field that contains over 8000 references[4].

Force Concept Inventory

A pivotal event in the field of conceptual understanding occurred when Halloun and Hestenes synthesized research on understanding (and misunderstanding) of concepts of force and motion to create the Force Concept Inventory (FCI)[5]. Consisting of 29 multiple-choice questions, the FCI assessed a student's understanding of Newtonian concept of force and requires a student to select between Newtonian concepts and common sense alternatives. It focused on six conceptual dimensions: Kinematics, Newton's First Law, Newton's Second Law, Newton's Third Law, Superposition Principle, and Kinds of Force. Results from the FCI showed that students may struggle with qualitative problems but end up doing well on conventional tests[5]. The main focus of FCI in the literature has been on improving teaching of a physics course and not specifically on the preparation of students for follow-on courses.

A more recent alternative to the FCI is the Force and Motion Conceptual Evaluation (FMCE). Covering a wider variety of topics than the FCI, such as more questions on kinematics, the 47 multiple-choice question inventory also determined that using new techniques provides significant gains over teaching with a traditional lecture approach[6,7,8,9].

Conceptual Understanding of Statics

In statics, objects do not move. Therefore, many of the questions in the FCI, while relevant to statics, do not directly assess student knowledge of statics. Therefore, researchers have worked to explore how learners understand statics. Developed in the late 1990s, the Math-Statics Baseline (MSB) Test explored basic mathematics skills taught in high school or first-year calculus[10].

Composed of 10 questions related to mathematics and 10 questions related to statics, the results for the mathematics portion were very high, but few statistically significant differences between test groups were found. Further work on the MSB included expanding the statics portion of the test[11]. In approximately 2003, the Statics Skills Inventory was released with 12 questions relating to skills learned in statics[12]. It assessed the student skills critical to the mastery of statics and not simply conceptual knowledge and focused on four groups of skills: vector manipulation, modeling and free body diagrams, equilibrium equations, and manipulation of forces and force systems. As of 2005, the authors were working on developing questions highlighting one skill as opposed to typical engineering problems requiring multiple skills to solve[12].

Around the same time as the work on Statics Skills Inventory in 2002, the Statics Concept Inventory (SCI) was developed to detect errors associated with incorrect concepts in statics[13]. The authors of this inventory took at different approach than the Statics Skills Inventory as they evaluated the conceptual knowledge and not skill-level knowledge. Authors of the inventory stated that mathematical skills were needed for statics, but they were not part of conceptual content covered in the SCI. Through the current version containing 27 multiple-choice questions, the SCI focused on five groups of conceptual errors: free body diagrams, static equivalence between different combinations of forces and torques, type and direction of loads at connections, limit on friction forces, and equilibrium conditions. The largest errors by students were reported on questions pertaining to constraints and constraint forces[14].

Both the Statics Skills Inventory and the SCI were designed to be post-assessments to quantify the amount of material students learned in statics. In a similar way, the Statics Competency Test (SCT) evaluated the material learned in statics but was used as a pre-assessment to the follow-on course[15]. First used in the fall of 1984, the SCT was given as a precursor to students entering the Strength of Materials course to see how much students retained knowledge learned in their statics course. Students scored an average of 39.4 percent on the test, which was an unexpected result. The expectation by a number of statics instructors was that a minimum average score of 50 percent would not be unlikely. The authors concluded that grading standards were too lenient on average.

Mechanics Baseline Test

In addition to how learners understand concepts in physics mechanics, including statics, physics and engineering faculty members are also interested in learner abilities to solve physics problems. To assess these abilities Hestenes and Wells[16] developed the Mechanics Baseline Test (MBT). It complements the FCI. Questions on the MBT focus on learner abilities to solve physics problems in three areas of physics mechanics: kinematics, general principles, and specific forces. It has 26 multiple-choice questions that, unlike the FCI, require that students perform computations to find answers to the questions. It is intended to assess student learning after instruction in mechanics. Using both the FCI and MBT, the authors determined “a good score on the Inventory [FCI] is a necessary but not sufficient condition for a good score on the Baseline” (p. 5)[16].

Work on conceptual understanding, including the FCI, the FMCE, the SSI, and SCI, has provided considerable information about how students understand (or misunderstand) concepts

in many different subjects[5,6,7,8,9,13,14,15]. In addition, the MBT provides information about abilities to solve problems in physics mechanics[16]. However, the research does not provide explicit articulation of what engineering faculty members who teach core engineering courses that require physics mechanics as prerequisite knowledge think their students should know and be able to do at the beginning of one of these courses. Nor does the research shed light on how well students satisfy expectations of their faculty members. Therefore, this gap motivates the research described in the following sections.

Methods

To determine expectations of engineering faculty for the knowledge of physics mechanics and skill in applying this knowledge that students in their course should have to be successful, the authors identified a core, required, sophomore-level engineering science course in the mechanical engineering curriculum. While students complete several engineering courses in their sophomore-year, including statics and dynamics, materials, thermodynamics, and numerical methods, the course selected is a statics and dynamics course that resembles many courses in mechanical engineering curricula across the world because it is the most calculus and physics intensive. For mechanical engineering students, they are expected to apply what they learned in their first-year calculus and calculus-based mechanics physics courses, as well as the mathematics and physics they learned in high school. Also, the course is a direct prerequisite for more follow-on courses in different engineering programs, including being a direct prerequisite to five follow-on courses in the mechanical engineering curriculum. It also lies in the critical path to degree for students. Taught as a service course in the mechanical engineering department, over 1,300 engineering students per year enroll in the statics and dynamics course, or a similar course, from almost all engineering majors at the institution. In addition, since it is taught as a service course for many other departments, the curriculum is common among the different sections of the course, and standardized sets of exams are utilized. For these reasons, it is relatively easy to extract necessary data for comparison. The importance of this course in an engineering curriculum was conveyed by Danielson and Danielson[17] who determined, "Success in latter courses is directly correlated to success in statics."

Next, the authors asked engineering faculty members who teach the course for problems that illustrated the prerequisite physics mechanics knowledge and skills students should have mastered when they entered the course. The authors thought that asking for problems would be more helpful than asking for a list of topics and getting back a very long list from which it would be difficult to construct an instrument to assess student knowledge of these topics. Also, the problems would illustrate contexts into which students would be expected to transfer their physics mechanics knowledge. Sometimes students may know the physics concept or procedures, but they may not recognize that the problem requires what they know because the context of problem is unfamiliar or different than the context in which they learned the concept or procedure. The authors found asking for problems focused faculty members on their specific expectations for student physics mechanics knowledge and skills.

After receiving sample problems from five faculty members, the questions were analyzed to develop a set of learning outcomes that would reflect the knowledge and skills required to solve the problems. There was significant overlap among the problems, with respect to the knowledge

and skills expected. In addition, several of the problems submitted were actually mathematics-related skills and not directly physics mechanics skills. The resulting set of physics mechanics topics for which engineering faculty members expected student mastery are listed in Table 1.

Table 1. First-year Physics Mechanics Topics Determined by Engineering Faculty Members

Free Body Diagram
Newton's Second Law
Newton's Third Law

Using this set of topics and the original problems to guide the authors about the expectations of the engineering faculty members, the authors created a 16-question, alpha version of an instrument to assess student abilities with respect to expectations. Several of the problems came directly from the MBT since faculty had provided a limited set of direct physics mechanics-related questions. The instrument was then reviewed by two of the engineering faculty members who submitted problems, and they agreed the instrument contained the skills necessary to be successful in the course. The authors thought it would take about 30 minutes for students to complete, and the engineering faculty member who taught the statics and dynamics course during the summer of 2010 was willing to allocate 30 minutes of class time to administer the instrument. Also, students would not be allowed to use their calculators. Each of the 16 questions was multiple choice, and for each question, students were given space to work the problems. It was administered to a group of 41 sophomore-level engineering majors in the course on the first day of the summer of 2010 semester.

With such a small number of participants, this allowed each response to be evaluated for common mistakes to help in the revision process. While the work submitted was anonymous, interested students could include their e-mail address to have a customized report of their work sent to them. The results were then entered into Microsoft Excel and percent correct and incorrect were determined. A summary of the work was then sent to the professor. Instead of simply including percent correct and incorrect or the numbers breakdown by each item, the topics were summarized, and input was provided on where students were generally strong and where students failed to have an understanding. Administering the alpha instrument provided an indication of student performance in terms of the expected concepts and skills (see Table 2).

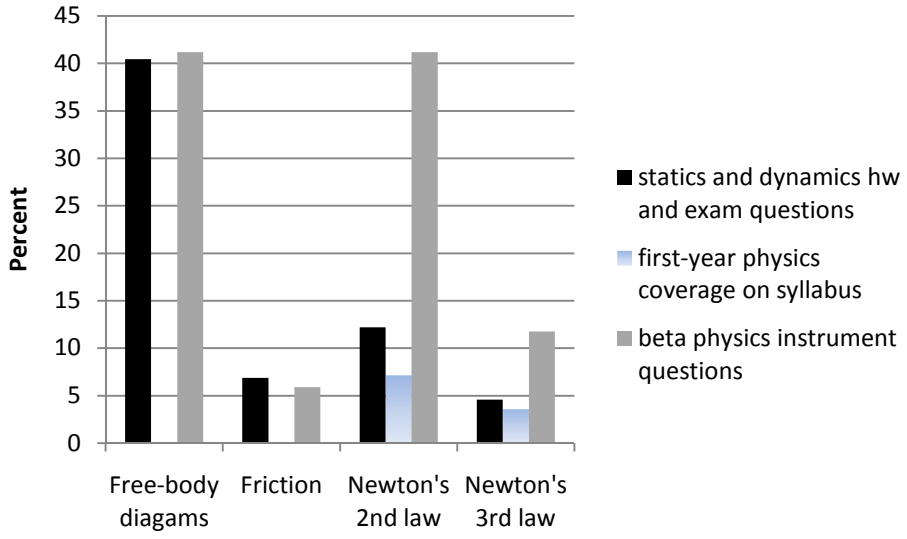
Table 2. Percentage of Students Answering all Questions in a Topic Correctly on Alpha Version

Topic	Number of Questions on the Instrument Assessing this Topic	Percentage of Students that got all of these Questions Correct
Free Body Diagram	4	22
Linear Momentum	4	29
Newton's Second Law	4	7
Newton's Third Law	2	37
Friction	1	93
Conservation of Energy	1	44

After results from the alpha version of the instrument were analyzed, the instrument was then revised. In addition, item responses and work shown from students were evaluated to determine if students properly understood what the question asked of them, how the responses compared to expectations, and appropriate answers to include in the next prototype.

Homework and exam problems were dissected to gauge what knowledge and skills in physics mechanics were needed to answer the questions. In addition to this analysis, two doctoral students in mechanical engineering analyzed a set of randomly selected problems to provide a check of the validity of the analysis. Analyzing homework and exam problems allowed the analysis to be based on actual evidence from an offering of the course instead of perceptions faculty members might have about what they wanted. From this analysis, a list of knowledge and skills in physics was compared to the original list[18]. After further review, it was determined that conservation of energy was not an essential skill for work completed by students in the statics and dynamics course. In addition, some of the questions dealing with linear momentum were not direct skills highly utilized in the course. Important physics mechanics skills resulting from the analysis of homework and exam problems included free body diagrams, friction, Newton's Second Law, and Newton's Third Law. Direct questions from the MBT were removed in the beta version. Three of the questions in the beta version were similar in theme to questions on the MBT and SCI but unique problems. The revised instrument was then reviewed by the engineering faculty members who submitted problems and other instructors teaching the same or similar course, and they agreed the instrument contained the skills necessary to be successful in the course. The resulting set of physics mechanics topics identified as necessary for student mastery are listed in Figure 1. In addition, the comparison between percentage of homework and exam problems covering the topics, percentage of time spent in first-year physics mechanics course on the topics according to course syllabus, and percentage of questions pertaining to each topic on the beta version of the physics instrument are detailed in the figure.

Figure 1. Alignment of First-year Physics Mechanics Topics



From the figure, serious alignment issues are evident between topics engineering faculty members utilize in the statics and dynamics course and included in the first-year physics mechanics syllabus. The course syllabus for the physics mechanics course details a course weighted in teaching kinematics, which is unbalanced when compared to the material taught in statics and dynamics. While this issue, along with others specific to the notations used in each of the classes, is recognized, it is out of the scope of this paper.

In fall of 2010, a beta second version of the instrument was given to three sections of the statics and dynamics course whose instructors would allow class time to administer the instrument. There were 264 students who completed the instrument. In addition, the instrument was administered to students in two aerospace engineering courses. The first aerospace course is equivalent to the first half of the statics and dynamics course, while the second aerospace course is equivalent to the second half of statics and dynamics course. These two aerospace engineering courses are taken exclusively by aerospace engineering majors. Including the aerospace students, the total number of students completing the physics instrument was 362 students. As with the alpha version, this instrument was given on the first day of the fall semester in each of the sections.

While the plan had been to administer the instrument with scantrons, they were not used for fear of time limitations in the classroom. Therefore, each question was multiple-choice, but students were allowed to denote their answers on each instrument. Students were given 20 minutes to complete the instrument and again were not allowed to use their calculators. Decreasing the amount of class time needed to administer the instrument seemed to make a significant difference in the willingness of faculty members to allow class time for the instrument to be administered. The beta version of the physics mechanics instrument had 17 questions.

As with the alpha version, a detailed summary of the results on the topics was sent individually to each faculty member with specific details included on their students. Students were also given the opportunity to include their e-mail address to have an individualized summary sent to them.

Table 3. Percentage of Students Answering all Questions in a Topic Correctly on Beta Version

Topic	Number of Questions on the Instrument Assessing this Topic	Percentage of Students that got all of these Questions Correct
Free Body Diagram	7	2
Friction	1	91
Newton's Second Law	7	6
Newton's Third Law	2	58

Results and Discussion

Once the instrument was administered, results from both the alpha and beta versions were evaluated in more detail. Evaluation, such as item difficulty index, overall results, and results on individual questions were addressed in greater detail.

Alpha Instrument

The item difficulty index measures the difficulty of a single test question. Calculated by taking the ratio of the number of correct responses on each question to the total number of students who attempted the particular question, the index ranges from 0 to 1. A larger value for the index signifies that a higher percentage of respondents answered the question correctly, so the item was easier for this population. If the index value is 1, this signifies that all of the participants answered the question correctly. If the index value is 0, no one was able to answer the question correctly. Therefore, a value of 0 or 1 does not discriminate very well. While there are a number of different possible criteria for acceptable values of the item difficulty index, a widely adopted criterion requires the value to be between 0.30 and 0.70 within+/-.20 of the optimum value of 0.50[19].

As viewed in Figure 2, the mean difficulty index of the responses in the alpha version of the physics instrument given in summer of 2010 is 0.52. Simply because responses to a question fall outside of the optimum range of 0.30 to 0.70 does not nullify the question, but it does cause concern for closer inspection. The two questions that show warrant further review are item #8 with an index value of 0.25 and item #2 with an index value of 0.93. Table 4 lists the two questions on the opposing ends of the histogram.

Figure 2. Item Difficulty Index for Alpha Physics Instrument

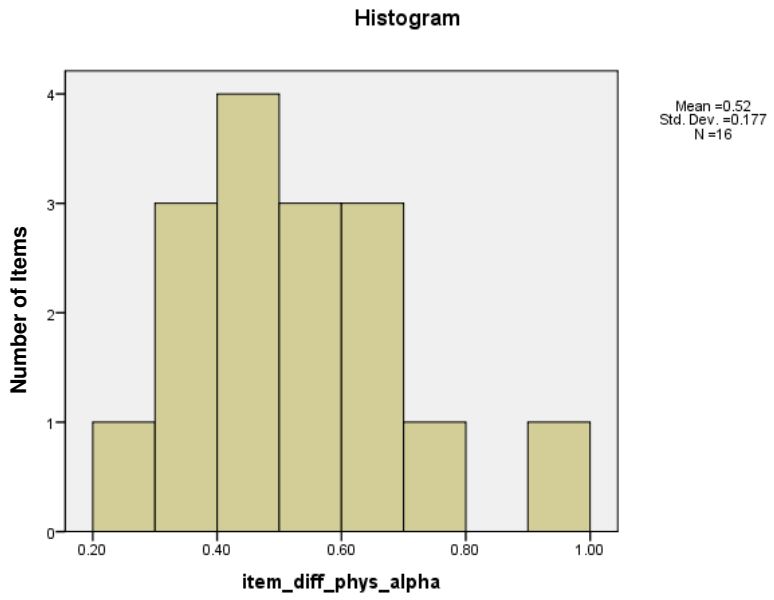


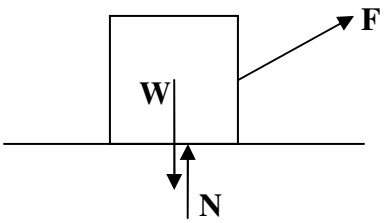
Table 4. Questions from Alpha Version of Instrument with Highest and Lowest Item Difficulty Index Value

Question #	Item Difficulty	Question Statement	Details

	Index Value		
8	0.25	A small metal cylinder rests on a circular turntable, rotating at a constant speed as illustrated in the diagram below. Which of the following sets of vectors best describes the velocity, acceleration, and net force acting on the cylinder at the point indicated in the diagram? (Figure 3 displays the cylinder on the circular turntable.)	Each of the answer selections had a large number of responses, which signified that students did not know how to solve this problem. There was not a particular common error.
2	0.93	A person pulls a block across a rough horizontal surface at a constant speed by applying a force F. The arrows in the diagram correctly indicate the directions, but not necessarily the magnitudes of the various forces on the block. Which of the following correctly describes the friction force on the block? (Figure 4 displays the configuration detailed.)	Most students answered the problem correctly. There were two common errors. 5% of students answered the friction force has the same line of action as the applied force F but in the opposite direction because every force on a free body diagram should have an equal and opposite force shown. 2% of students answered there was not a friction force because the block is moving at a constant speed.

Figure 3. Cylinder on a Circular Turntable from Question #8 on Alpha Instrument

Figure 4. Block Being Pulled Across a Rough Surface from Question #2 on Alpha Instrument



Beta Instrument

After changes to the alpha version of the instrument, the following results were found in the administration of the second version of the instrument. Figure 5 contains the item difficulty index for the items in the beta physics instrument. The three questions that show warrant further review are item #13 with an index value of 0.11, item #2 with an index value of 0.91, item #6 with an index value of 0.83, and item #11 with an index value of 0.80. Overall, items on the beta version were more difficult than items on the alpha version. Table 5 lists the three questions on the opposing ends of the histogram.

Figure 5. Item Difficulty Index for Beta Mathematics Instrument

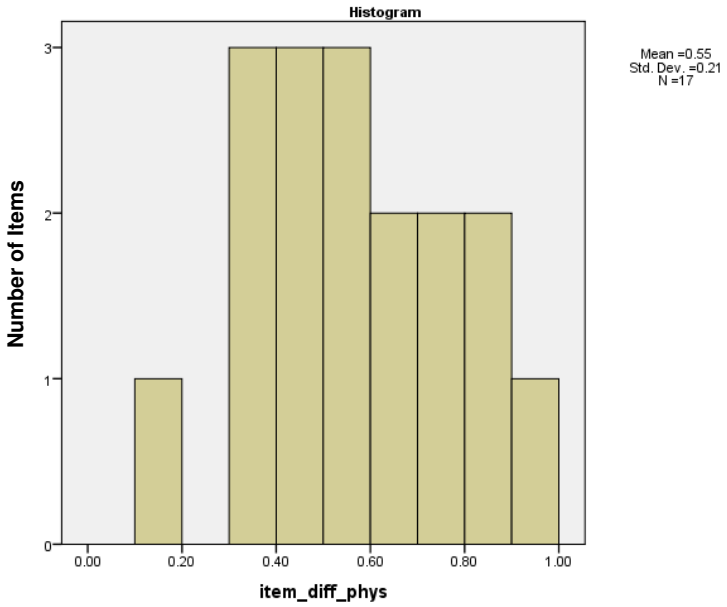


Table 5. Questions from Alpha Version of Instrument with Highest and Lowest Item Difficulty Index Value

Question #	Item Difficulty Index Value	Question Statement	Details
13	0.11	Different signs hang together outside a doctor's office.	60% of students included a force in between the two parts within the

		Each sign is denoted by a different letter. Each cable is labeled with a different number. Which is the most correct free-body diagram for the system containing signs B and D and the cable connecting them? (Figure 6 displays the sign configuration.)	overall system. 29% of students solved for the value of the variable and put it on the FBD instead of leaving it in terms of T for example for a cable.
2	0.91	A person pulls a block across a rough horizontal surface at a constant speed by applying a force P. The arrows in the diagram correctly indicate the directions, but not necessarily the magnitudes of the various forces on the block. Select the most nearly correct answer from the options below to describe the friction force on the block. (Figure 7 displays the configuration detailed.)	Most students answered the problem correctly. In this version, the answer choices were changed slightly. There were two variations on the friction force moving to the left to see if students could correctly identify why the friction force moved to the left. 3% of students answered that the friction force moved to the left because friction acts in the opposite direction to the externally applied force (instead of correctly stating it is because it opposes the direction of motion). Another 3% of students answered the friction force has the same line of action as the applied force F but in the opposite direction because every force on a free body diagram should have an equal and opposite force shown. 2% of students answered there was not a friction force because the block is moving at a constant speed.
6	0.83	A tennis ball moves such that its velocity as a function of time is described by the graph below. Which of the following graphs most accurately represents the ball's net force versus time association? (Figure 8 displays the graph detailed.)	Most students answered the problem correctly. The most common error made was by 11% of students who answered that the force versus time graph would be identical to the velocity versus time graph.

11	0.80	A crate containing two ornamental pieces, piece A and piece B, is picked up by an overhead crane. The cables holding the pieces are denoted by numbers 1 and 2. Each ornamental piece weighs 10 kg. If the pieces in the crate are moving upward at a constant speed of 3.0 m/s, how (if any) would the answer above in question #10 differ? (Question #10 asked when the pieces in the crate are not moving, what is the magnitude of force exerted on piece A by rope 2?) (Figure 9 displays the crate configuration for both questions.)	Most students answered the problem correctly. 14% of students selected the answer in #10 would be multiplied by 3 and then given in N. 3% of students answered it should be multiplied by 3^2 and then given in N. 2% of students selected the answer would be equal to 3 N, and a final 1% felt it would need to be divided by 3 and then given in N.

Figure 6. Sign Configuration from Question #13 on Beta Instrument

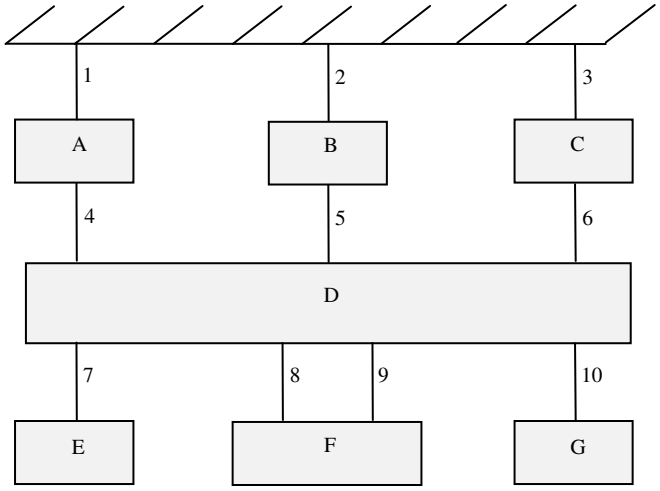


Figure 7. Block Being Pulled Across a Rough Surface from Question #2 on Beta Instrument

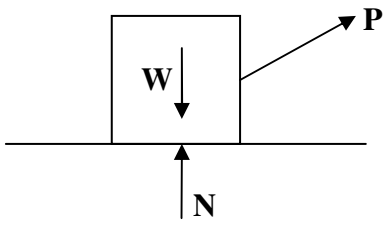


Figure 8. Graph from Question #6 on Beta Instrument

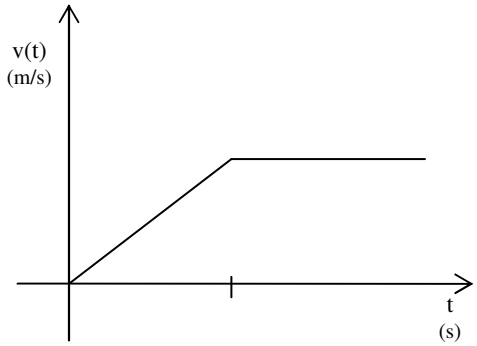
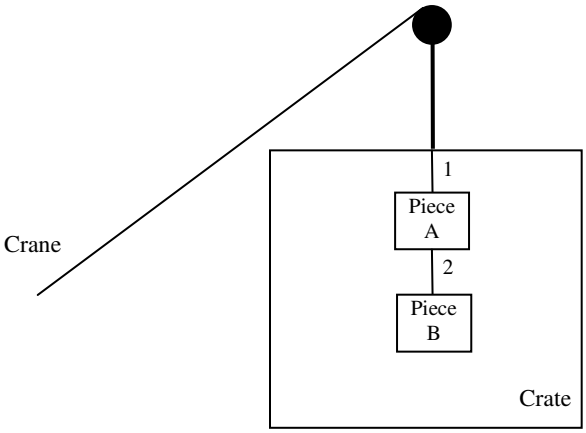


Figure 9. Crate Configuration in Question #11 on Beta Instrument



The two questions from the alpha version that were investigated further were changed on the beta version. Question #8 had asked students to select the correct direction for velocity, acceleration, and force on a cylinder. To gain further insight as to where students had trouble with circular motion and if they could accurately explain why they selected a particular direction, this problem was changed on the beta version. Students were required to not only select a direction for force on one question and acceleration on a second question but also distinguish between two possible reasons for the direction selected. This same format was used on the

problem dealing with friction, which was question #2 on the alpha version. Even with the adjustment, students overwhelming still answered the question on friction correctly.

Three areas on the physics mechanics beta instrument had less than 50% average of correct answers identified by students, which causes concern. The lowest average received was on a stationary free-body diagram in question #13, which was discussed above in Table 5. Students also had a difficult time with the two circular motion problems on the instrument. Only 34% of students could correctly identify the direction of force of a child sitting on a merry-go-round turning clockwise at a constant speed. Problematic is the fact that 37% of students felt acceleration would be zero because the circular object is turning at a constant speed. The third area causing concern dealt with free-body diagrams including a free-fall condition. Approximately 17% of students selected an answer choice that included a normal force. Answer selections including a velocity vector was selected by 39% of students.

The average response from 362 students on the beta version of the instrument is 52%. This value was considered much lower than the targeted 75% number. Looking at the results, two students scored a perfect score with a student answering only two questions on the instrument correctly and earning a score of 12%.

Conclusion

After administering the instrument and analyzing the results, the authors were able to inform the participating engineering faculty members of the strengths and weaknesses of their students related to the topics covered in the instrument. This knowledge allowed the faculty members to have a better idea of the background of the students in their class. Overall, the students scored lower than expected on the beta instrument. The details of why students performed poorly are outside of the scope of this paper. The instrument identified three significant problem areas where students lack the skills from first-year physics mechanics that are needed for a sophomore-level statics and dynamics course. The areas are (i) free-body diagrams in which the free body is stationary, (ii) free-body diagrams in which the free body is in a free-fall condition, and (iii) forces and acceleration specifically related to circular motion.

Properly identifying skills needed from first-year physics mechanics provides a better mechanism for discussing how to meet the needs of students in a sophomore-level statics and dynamics course. By understanding with what skills a student enters the course, engineering faculty can make better use of teaching time and evaluate what additional resources might assist learning of the material. For example, several faculty members commented that additional classroom time could be spent on circular motion after the high number of students that only associated acceleration with speed. Likewise, the results allow physics mechanics faculty to be able to determine the utilization of the material they are teaching and be aware of different notations engineering faculty might use for the same concept. The instrument is even useful for students as they are able to improve skills necessary for their success. During the administration of the instrument, students were able to receive a personalized set of results for their review upon request, and approximately 70% of students asked for this feedback.

Faculty members stated they would be willing to use the instrument again in future classes to determine the first-year physics mechanics skills their students know upon entering their class. Future work with the instrument will compare the results from the instrument with final success in the course to see the extent of physics mechanics preparation needed to be successful in engineering. The desire is to be able to alleviate the misalignment between the skills engineering faculty at the sophomore-level felt students should enter their course with and those students actually had obtained.

Questions for future research include studying relationships between student responses on the instrument and performance on examination questions in the course. That is, are there relationships between student knowledge and skills with respect to physics at the beginning of the statics and dynamics course and their ability to solve problems in the course?

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