Assessing a Conceptual Approach to Undergraduate Dynamics Instruction

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Introduction

Engineering disciplines have historically been taught via lecture, where the professor presents material and performs calculation-based examples and the students take notes. Such an approach can be beneficial in that it allows material to be covered quite quickly, but it may not provide the deeper understanding and the higher-order skills that are required of today's modern engineers. Specifically, this traditional approach to instruction can be effective in transferring procedural knowledge such as selecting the correct equation and following the steps of a rote procedure, but it may not achieve the other goals desired of instruction. Since traditional assessment involves performance by students on written, calculation-based exams where the problems can be mapped by students to other problems that they have seen in homework and class, students can often find the "correct" answer while lacking fundamental understanding and higher-order skills. Many studies have been performed in the STEM fields that identify such deficiencies. As of 2009, the database of (Duit, 2009) has compiled over 8300 studies identifying student misconceptions in STEM fields.

Over the past few years, the authors have gradually updated the instructional approach they employ in their undergraduate dynamics courses in order to address deficiencies they have observed directly and that have been identified in the literature. This has involved displacing some lecture time previously spent on performing traditional calculation-based examples, and replacing that time with more conceptual problems, activities, and discussion. The conceptual problems can be solved with minimal calculation and employ a multiple choice format. Students are given time in class to answer such problems and then their solutions are used as a jumping off point for discussion or further instruction. The additional instruction is used to address deficiencies the students exhibited while answering the conceptual problems. This general approach is sometimes referred to as the *Peer Instruction* technique (Mazur, 1997) and has been demonstrated to achieve improvements in students' conceptual understanding in many fields including physics (Crouch & Mazur, 2001). One means for assessing student conceptual understanding is through the use of *Concept Inventory Tests* (Hestenes, Wells, & Swackhammer, 1992) (Gray, Costanzo, Evans, Cornwell, Self, & Lane, 2005). These exams employ concept-based, multiple-choice questions, much like those employed in Peer Instruction and that the authors have implemented in their dynamics courses.

In addition to the use of concept-based equations, the authors have also attempted to involve their students in activities during class time. These activities included things as simple as having the students perform calculation-based, homework-type problems during class time. The authors have also had the students perform more open-ended, design-type problems in class. In addition to performing paper and pencil activities, the authors' have also shown their students animations and videos of experiments. Recently, the authors' have also begun employing a limited number of *Inquisition-Based Learning Activities* that involve simple experiments accompanied by discussion (Thacker, Eunsook, Trefz, & Lea, 1994) (Self , Widmann, & Prince, 2013).

In order to accommodate the extra class time that such activities require, the authors' have added a weekly 1-hour recitation section to their courses. More details concerning the authors' pedagogical approach can be found in the prior paper (Hill & Plantenberg, 2012).

While the techniques employed by the authors have been shown to improve student learning outcomes in several different venues, the authors will present in this paper results from their own courses to assess their specific implementation of the techniques. Furthermore, these assessments will add to the current body of knowledge regarding student performance in undergraduate dynamics courses in particular, and in engineering courses in general. One source of assessment data is a common final inspired by the Fundamentals of Engineering Exam (part of the professional licensure process). This final has been given to every dynamics class at the University of Detroit Mercy (UDM) since 2005 and serves as a good measure of students' attainment of more procedural knowledge.

More recently, the authors' have also begun to give oral quizzes on open-ended design problems that seek to assess students' conceptual understanding, as well as their higher-order thinking and problem solving skills. Furthermore, the students' performance is assessed compared to how they perform relative to two "experts" who were also given the quizzes. This assessment seeks to better identify what exactly the desired student outcomes are. Typical assessment focuses on facts and procedural knowledge, but there is an ever increasing need for students to be able to master what are sometimes referred to as "soft skills," things like communication and problem solving. The importance of such skills in an increasingly competitive global market for engineers is evidences by a range of government reports (National Academies of Engineering and the National Academies, 2004) (National Academies of Engineering and the National Academies, 2006), by ABET accreditation standards, and even in popular literature (Friedman, 2005). The results of this more qualitative assessment is very preliminary, but appears especially promising for identifying student deficiencies and directions for future modifications to the authors' overall approach to pedagogy. Finally, survey data is employed to assess students' attitudes toward these various instructional approaches.

Common Final Data

The first measure of the effectiveness of the conceptual approach to instruction that the authors have been employing is their students' performance on a common final exam. The exam is inspired by the Fundamentals of Engineering Exam in that the problems are relatively short such that each question covers basically one concept. The problems have a multiple-choice format, but students can earn partial credit with their work. The problems are more traditional and calculation-based and don't directly assess physical insight and high-order reasoning skills, but they do test the students' procedural knowledge and may indirectly indicate the other skills.

This exam includes 10 problems that cover the basic topical areas taught in the course, they are listed in the following. Furthermore, Figure 1 shows average student scores for each problem on the common final, including bars representing 90% confidence intervals (assuming a normal distribution of scores). The data compares student performance prior to the adoption of the conceptual approach to pedagogy (2005-2010) to student performance following the change (2011-2012). This data is only for sections taught by Professor Plantenberg since Professor Hill did not have a sufficient number of data points prior to the adoption of the new teaching methodology. No data exists for 2013 because Professor Plantenberg was on sabbatical. In all, the Before data set includes scores from 96 students and the After data set includes scores from 26 students. Due to some changes in the final exam, the size of the Before set for Problem 7 and the After set for Problem 9 are smaller.

Problem 1 – Particle – Kinematics, Rectilinear Motion
Problem 2 – Particle – Kinematics, Planar Motion (Normal Tangential Coordinates)
Problem 3 – Particle – Kinematics, Planar Motion (Projectile Motion)
Problem 4 – Rigid Body – Kinematics (Velocity)
Problem 5 – Rigid Body – Kinematics (Acceleration)
Problem 6 – Particle – Kinetics, Newton's Laws
Problem 7 – Rigid Body – Kinetics, Newton's Laws
Problem 8 – Particle – Kinetics, Work-Energy
Problem 9 – Rigid Body – Kinetics, Work-Energy
Problem 10 – Particle – Kinetics, Impulse-Momentum

Examining the data, Professor Plantenberg's students observed an overall improvement in average score on the final exam from approximately 76% to 85%. Furthermore, as shown in Figure 1, students performed better on average on 7 of the 10 problems. While the data from Professor Hill's courses is limited, his students' average score on the final did improve from 73% to 78%. Additionally, Professor Hill saw his drop rate in the course decrease by approximately 50%.

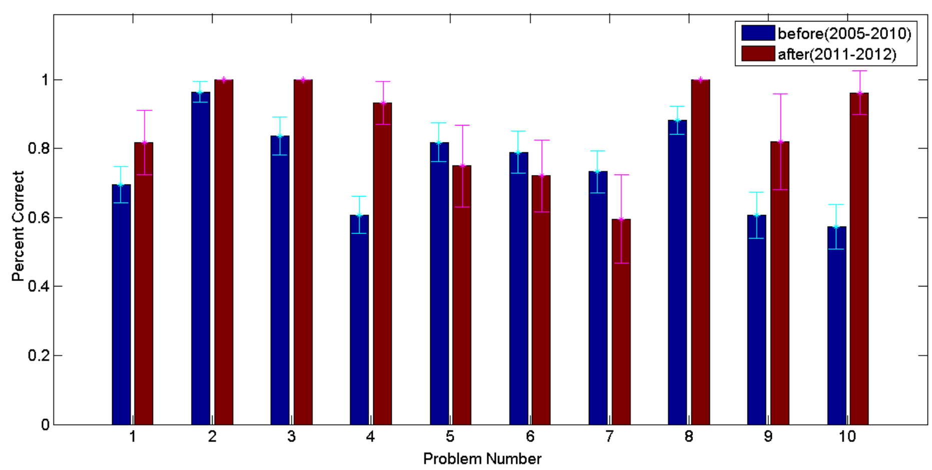

Figure 1 Common final data for Professor Plantenberg including 90% confidence intervals

The improvement in student performance on the final exam demonstrates the new conceptual approach to pedagogy has promise. It would be interesting to gather additional data and to look more closely at other factors affecting student performance. For example, the adoption of the new pedagogical approach was accompanied by the addition of a weekly 1-hour recitation section, in addition to the standard 75-minute lecture meetings that occur twice per week. The thought was that the recitation would reduce the amount of time students spend outside of class on the course, but this effect has not been quantified.

Qualitative Assessment Data

In this section, student performance on two oral quizzes that have been given in the last two offerings of Professor Hill's course will be examined. Student performance on these assessments will be examined in order to identify student strengths and deficiencies in terms of their physical insight and high-order reasoning skills.

The two oral quizzes that were employed are open-ended, design-type problems that are meant to assess student learning in a context that approximates what they will see in industrial practice. Furthermore, the students' performance is assessed compared to how they perform relative to two "experts" who were also given the quizzes. In this case, the experts were faculty who have experience teaching and doing research in the area of dynamics, but who had no prior experience with the particular systems that were the subjects of the two quizzes. The idea is to identify what an expert in the area of dynamics looks like in terms of their skills and knowledge, and then to adapt dynamics instruction to have students more closely achieve the ideal (expert performance).

The quizzes have been given in two offerings of the course. In the Fall of 2012, the quizzes were given to 11 students. This process helped to tune the content and delivery of the quizzes. The results of these quizzes will be employed anecdotally, but a close read of the results of these assessments will be saved for the results from the Fall of 2013 where the quizzes were given to a class of only 3 students. We will refer to these students as Student A, Student B, and Student C. These students represent a reasonable range, having earned grades of B+, B-, and D in the course, respectively.

Topic #1: Rigid-Body Kinematics

The first topic that was qualitatively assessed was Rigid-Body Kinematics. The Oral Quiz used to assess this topic employed the amusement park ride shown in Figure 2 where the primary structure (in yellow) is driven at a constant angular velocity and the riders sit in individual cars that are free to rotate relative to the structure. The problem posed to the students was to determine the constant angular velocity ω with which to drive the primary structure such that the peak accelerations experienced by the riders are kept below some provided limit. The students are told that they have access to the physical dimensions of the ride and that they have data representing typical angular velocities and accelerations of the cars for a range of different riders and conditions.

In preparation for this quiz, the students were presented with a range of calculation-based mechanism-type problems as in-class examples (slider crank, four-bar mechanism), in addition to some concept-type problems described earlier. Furthermore, the students were presented some animations of mechanisms, and solved an open-ended design problem as a group in the recitation section (based on the kinematics of an omni-directional ground robot).

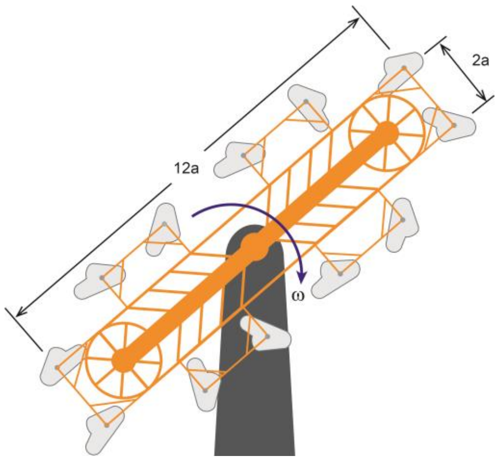

Figure 2 Amusement park ride system employed for oral quiz #2

For the assessment of the quiz, the performance of the two experts (in addition to the authors' evaluation of the given problem) was used to identify elements of a successful solution. The students' performance was then assessed based on how many elements of a successful solution they were able to correctly generate. Tracking these elements could be done in a number of ways, for example, with a simple checklist or table. In order to help make a solution easier to comprehend at a glance, it was decided to express the rubric as a concept map (Wallace & Mintzes, 1990) (Coppola, 2010).

The concept map generated for this problem is shown in Figure 5. If the student generates a piece of the solution independently, they receive full credit (1 point) and the element is marked green in the map. If the student is given a hint, they receive varying levels of partial credit and the element is marked orange in the map, the bigger the hint, the deeper the shade of orange. The advantage of this approach is that it allows each student's performance to be quantified. The disadvantage is the concept map doesn't track the solution process well. Since this quiz was given earlier in the course when not a lot of material had been covered, it seemed quite apparent to students that it was a kinematics problem and there wasn't a lot of thought given to what approach to take.

Roughly classifying student performance on the quiz, the weakest students had a difficult time starting the problem. Even though the students had seen examples, done homework problems as well as a written quiz on this topic, they couldn't translate what they knew to this system because they had not done any problems with an amusement park ride before. The interviewer would generally need to show the student how the two bodies were analogous to two arms of a mechanism that were pinned together. Another category of students were readily able to identify which equations to use, but didn't always have the best understanding of what the equations meant physically. These two groups of students could sometimes hide their lack of understanding on a written homework or exam problem, but it generally became apparent during the oral quiz. This is exemplified somewhat by Table 1where Student C was able to do well on the related problem on the written final exam by choosing the correct equation, plugging in the correct numbers, and performing the calculation correctly, but did not do well on the oral quiz. In this class and in the Fall 2012 class, there were instances where a student did well on a traditional, calculation-based problem, but did not do well on the open-ended oral quiz. The reverse of a student doing well on the oral quiz, but poorly on the more traditional assessments was generally not observed.

Table 1 Summary of rigid-body kinematics assessment

	Homework Problem	Written Quiz	Oral Quiz	Final Problem #9
Student A	+10/10	+9.5/10	+20.5/25	+8/10
Student B	+6/10	+5.5/10	+18.25/25	+7.5/10
Student C	+2/10	+3/10	+5/25	+10/10

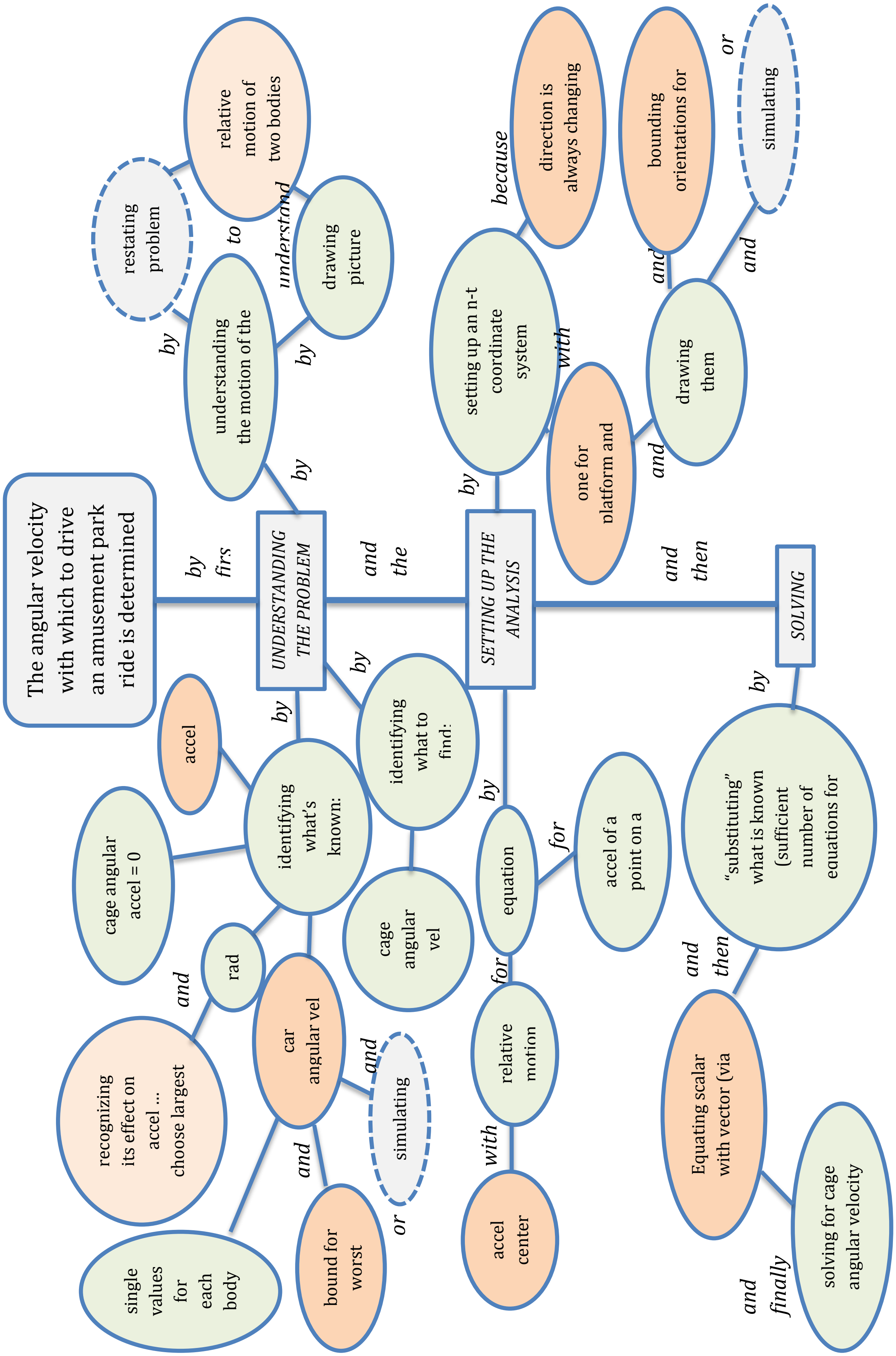

Figure 3 Concept map for Student A on oral quiz #1

The strongest students, such as Student A whose concept map is shown in Figure 5, were able to apply the equations correctly and seemed to have good physical intuition concerning their meaning. However, they struggled to deal with ambiguity and to make simplifying assumptions. For example, how to deal with the fact that there were multiple cars on the ride, that there were multiple coordinate frames that were constantly moving relative to one another, and that they were not given specific values for the angular velocity and angular acceleration of the cars, but were rather given sets of data for different riders and conditions.

This lack of ability to make simplifying assumptions is what set the best students apart from the two experts. Another difference was that the two experts both quickly jumped to using statistical analysis or simulation in order to deal with the empirical data on the cars' motion they had been given. None of the students thought to do this, even though the Fall 2013 class had been presented with some material on employing numerical approximation techniques. Finally, the two experts showed a much greater facility with equations and would do things like converting different reference frames to the same reference frame or even generating a closed-form expression for calculating the answer. The students were much more likely to speak conceptually about what they would do, or what would cause the greatest acceleration, rather than generating actual mathematical expressions.

Topic #2: Rigid-Body Kinetics

The second broad topic that was qualitatively assessed was Rigid-Body Kinetics. The oral quiz used to assess this topic referenced an orbiting satellite, such as the one shown in Figure 4. Specifically, the students were asked to make three design decisions where the goal was always to minimize the amount of fuel used by the satellite's thrusters. The three questions were: (1) where should you place a heavy battery within the structure of the satellite, (2) where should you place the satellite's thrusters to achieve pure translation and pure rotation of the satellite, and (3) how large do the thrusters need to be to achieve any orientation of the satellite in 60 seconds.

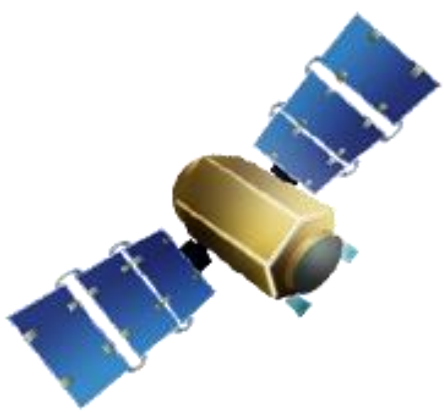

Figure 4 System employed for oral quiz #2

The students' preparation for this quiz was similar to the first quiz in that the students had seen a range of calculation-based and conceptual examples regarding such topics as moments of inertia and induced moments, as well rigid-body kinematics, Newtonian mechanics, and work-energy. The students had been introduced to rigid-body impulse-momentum topics, but they had not yet performed the associated homework and assessments. Furthermore, the students had performed an Inquisition-Based Learning Activity regarding rigid-body work-energy principles.

For this oral quiz, a different type of assessment was chosen than that employed for quiz #1. Specifically, we chose for this quiz to employ a modified version of a coded interview (Glaser, 1992) (Coppola, 2010) in order to assess the students' solution process, rather than just checking off elements of a successful solution. This approach was chosen since each student could address the problem (in particular question (3)) in a number of ways.

Figure displays the coded interview generated from Student A on oral quiz #2. This map attempts to identify what the subject was doing during each 30 second chunk of the interview. The three top rows capture the subject's processing of the question, while the remaining rows capture the subject's response. The correctness of a response is captured through color coding. Red indicates what the subject is saying is wrong, Orange indicates the response is either partially incorrect or partially unclear, while Green indicates a correct and justified response. Additionally, black bars between individual cells capture places where the interviewer intervened. Small bars indicate small questions that attempt to draw the subject out, such as, "what do you mean by …," "why do you think that …," etc. Long black bars indicate a significant hint that the interviewer provided in order to keep the quiz moving.

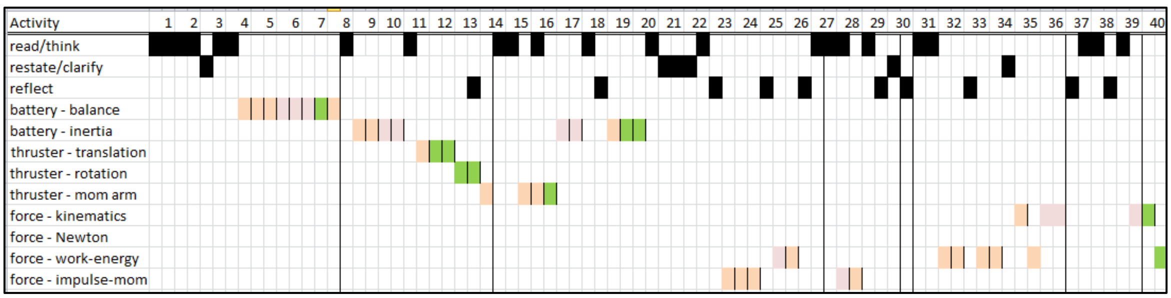

Figure 5 Coded interview for Student A on oral quiz #2

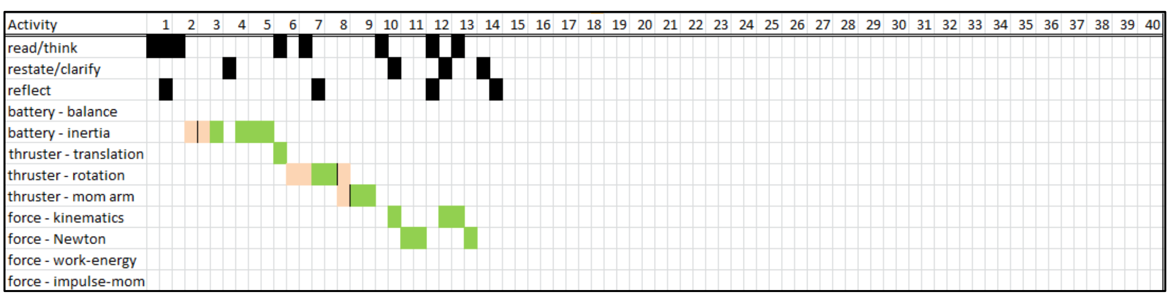

Figure 6 Coded interview for Expert #1 on oral quiz #2

Comparing the student interview in Figure and the expert interview in Figure , two things stand out. One, the student interview is longer and more meandering. You can see that the student spends more time thinking/clarifying/reflecting than the expert, and you can see that the student's solution/explanation often begins incorrectly before converging to a correct answer. With the expert, even the orange cells reflect the subject clarifying their response, rather than correcting an incorrect response. The second difference is that the student interview involves much more intervention. This involves not just small prodding, but significant hints as well. If the subjects were allowed more time overall, or if the quiz itself was less complex, it is possible that the student subjects could be given more latitude to figure things out themselves, rather than the interviewer feeling the need to step in.

An interesting element of the students' interviews is that many of them had trouble making the connection between the battery's placement and the overall moment of inertia of the satellite on their own. Many students wanted to place the battery at the center in order to achieve "balance."

Only with a leading question, such as, "if you could break the battery up into individual cells, would they rather place the cells symmetrically around the outside of the satellite or at the center," did they make the connection to mass moment of inertia.

A second interesting aspect of the interviews is that the students struggled with the third question regarding sizing thrusters to re-orient the satellite to any position within 60 seconds. This question was particularly challenging because some information wasn't directly given, and any of three kinetics approaches that they had learned could be applied (Newtonian mechanics, work-energy, or impulse-momentum). This ambiguity caused the experts no trouble and they would just begin with which ever approach seemed easiest at the moment. The students would become almost paralyzed, and even with encouragement, they would start and stop. This can be seen by the coded interview in Figure where the student initially chooses impulse-momentum because there is a time limit, but then stops and switches to work-energy because there is an angular displacement. Even then the student gets intimidated because angular velocity isn't given and because the distances aren't explicit. Only with some coaxing can they reason through the problem and bring in some of their knowledge of kinematics. Also, all of the students considered only planar motion of the satellite and didn't consider all three dimensions, one expert did so explicitly.

Student Attitudes

Aside from student learning outcomes, student attitudes toward the more conceptual and active approach to instruction employed in this work are also important to understand. In particular, student satisfaction in the introductory engineering curriculum can contribute to student retention. For example, Professor Hill saw his drop rate decrease by 50%.

In the Fall of 2012 and Fall of 2013, Professor Hill gave a supplemental survey, that while not anonymous, did give some good feedback. Of the 14 students surveyed, all 14 students indicated that the approach of the course "worked" for them. Some example comments include: "I didn't mind the oral quizzes, and I liked the variation in the class (ie- doing activities, oral quizzes, written quizzes, etc.)," and "I like the mix of theory and example problems." Some of the students did express a desire for more numerical examples, but they did not dislike the conceptual problems and activities. An example of such a comment is "Yes, it [the approach of the course] allows me to grasp the fundamentals, however, I would like more numerical examples where we walk through how to do the problem."

Conclusion

Overall, the results of this study indicate that a more conceptual and active approach to dynamics instruction may produce better learning outcomes. This conclusion is indicated by the improvement in the performance on the common final exam administered by the authors to their classes. These results primarily reflect an improvement in procedural knowledge and skills. It would be desirable to obtain further data and to better control for the overall time investment of the students.

It would also be desirable to apply the techniques of the open-ended oral quizzes to a more traditional dynamics course, where conceptual questions and activities were not employed. Even without a comparison "control" group, the results of the qualitative assessment did offer some glimpses as to how our students may be lacking in preparation as compared to "experts." For example, the students demonstrated a lack of skills and knowledge of numerical techniques to deal with problems that they couldn't solve analytically. Furthermore, the students didn't seem very adept at making and justifying simplifying assumptions, or dealing with problems with multiple feasible solution procedures. The results of these investigations will be employed to help further adapt the authors' instructional approach.

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