A Conceptual Approach to Undergraduate Dynamics Instruction: A Work in Progress

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Abstract
This paper outlines a new comprehensive approach to the instruction of dynamics at the undergraduate level. The proposed approach attempts to improve students' understanding and retention of the instructional material as well as strengthening the connections the students are able to make between the theory of the class and the real-world problems to which the theory will ultimately be applied. The basic approach espoused here puts a greater focus on the underlying concepts, rather than detailed calculation, and attempts to expose students to the individual topics of the course using different learning modalities. This paper outlines the proposed approach to dynamics instruction and offers examples of the materials that have been developed. This paper also offers suggestions on how to fit these extra materials and activities into the existing credit structure of a typical undergraduate dynamics course. Finally, the paper discusses some preliminary experiences from the introduction of such techniques and proposes some future work to be done in this direction.

Overview
The subject of dynamics is often a difficult one for undergraduate students to master. One source of this difficulty is the great number of permutations of problems that exist. Students must have a firm grasp of the underlying principles; they cannot simply memorize a cookbook approach to solving problems. It is also difficult to solve real-world problems because of their complexity. Obtaining the right level of abstraction and knowing what can be neglected and what can't are difficult tasks for even the most seasoned engineer.

In order to overcome these difficulties, the authors propose placing a greater emphasis on concepts and involving students more actively in the learning process so that they may build physical intuition for themselves. With a greater understanding of the underlying concepts, the students will then be able to solve more traditional calculation-based problems with greater confidence and success. This theory of instruction is gaining acceptance and is espoused by other instructors of physics and dynamics as exemplified by the use of *concept inventory tests* (Hestenes, Wells, & Swackhammer, 1992) (Gray, Costanzo, Evans, Cornwell, Self, & Lane, 2005) and *peer instruction techniques* (Mazur, 1997) (Crouch & Mazur, 2001). The techniques described in this paper adapt and add to such existing work.

This paper also describes the authors' attempts to make problems more realistic and to tie the work performed by the students more clearly to the underlying physical world that is being modeled and analyzed. This is accomplished by having students more explicitly consider how they are modeling physical phenomena and what the limitations of their models are. An attempt is also made to tie the theory to the real-world through the use of demonstrations and activities.

This paper outlines the proposed approach to dynamics instruction and offers examples of the materials that have been developed. This paper also offers suggestions on how to fit these extra materials and activities into the existing credit structure of a typical undergraduate dynamics course. Finally, the paper proposes some future work to be done in this direction.

Conceptual Examples

The authors of this paper recall clearly how as students they were taught engineering, including the subject of dynamics. A typical lecture would consist of a short introduction of some new theory and then the majority of the class would be spent going through a couple of detailed examples applying this new theory. The examples covered in class would be similar to those problems assigned in the current homework assignment and would involve a fair amount of calculation. A limitation of this approach is that the length of the examples constrains the number of problems that can be demonstrated in a typical class period. Furthermore, the amount of calculation involved in the problem can obscure the relevant new concepts that the example is meant to demonstrate. Finally, the learning process in such a lecture can be primarily passive. The majority of the class period involves students furiously trying to transcribe the growing lines of calculations that the instructor is writing on the board. The students are left precious little time to consider the material that they are copying down, even if an instructor stops periodically to ask questions and involve the students in the solution process. Often only a handful of the stronger, more outspoken students in the class will participate while the remaining students sit passively back.

An alternative to presenting exclusively calculation-based examples in class is to employ what we will refer to as *conceptual examples*. These examples are meant to be solvable without significant calculation and are meant to illustrate a single new concept. The advantages of this approach are that each problem can be covered in a shorter amount of time thereby allowing more problems to be covered and allowing more time for the students to think. Furthermore, with these examples the relevant new concept is at the forefront and isn't lost in the other details of the problem. Figure 1 depicts one such example conceptual problem.

The conceptual example shown in Figure 1 attempts to force students to build understanding of the concept of mass moment of inertia. Mass moment of inertia is a quantity that is typically calculated numerous times during a course in dynamics without students giving much thought to what the quantity represents; the students just look up an equation in a table and plug in numbers. This conceptual example forces the students to consider the idea of mass moment of inertia explicitly. In this case, students are first introduced to the topic of mass moment of inertia for a system of particles where each particle has mass m_i and is a distance r_i from the reference point O. Therefore, the mass moment of inertia of the system is $I_o = \Sigma m_i r_i^2$. The intuition gained from this introduction can then be applied to rigid bodies. Since each of the bodies in the problem of Figure 1 have the same mass, the bodies will have different inertias based on the distribution of that mass. Specifically, since the rotational inertia is proportional to the mass, but proportional to the distance squared, those bodies whose mass is on average distributed farthest away from the reference point will have the largest mass moment of inertia. For the given example, the ranking from greatest to least mass moment of inertia is then *C.* hoop, *B.* disk, *A.* sphere, and *D.* bar.

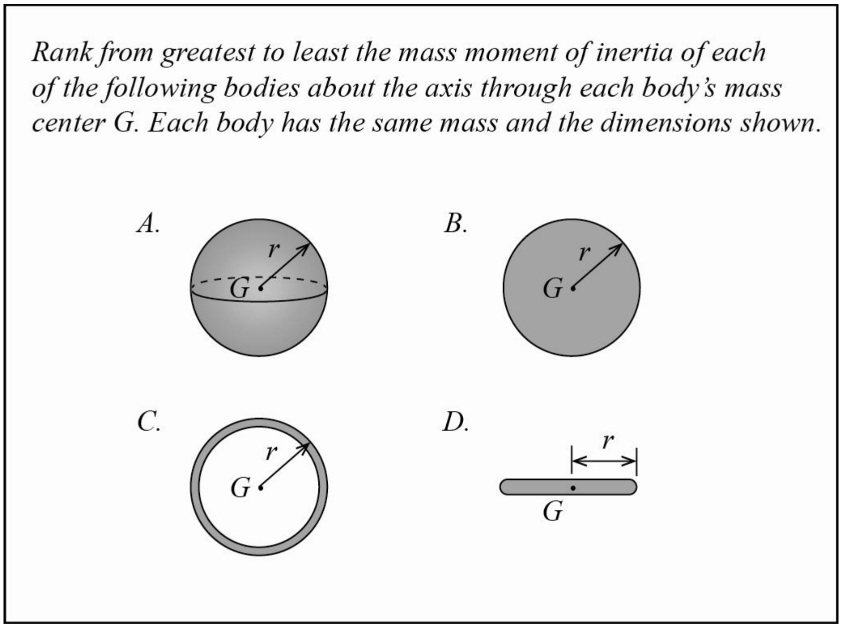


Figure 1 Representative conceptual example

As stated previously, the brevity of these conceptual examples allows students more time to absorb and reflect on the concepts in class. In general, they allow more time for the students to discuss the concepts and ask questions of the instructor and their fellow students. The promotion of a more active approach to learning is indicative of a peer-instruction approach to education (Mazur, 1997). For example, within a given class period the conceptual example shown in Figure 1 could be presented to the students and then the students given a couple of minutes to attempt to answer the problem on their own. A couple of additional minutes could also be allowed for students to discuss their answers with a neighboring student so that they may correct or solidify their reasoning. After this time has been taken, the instructor can then poll the class either through the use of a personal response system ("clickers")[1] or more informally by a show of hands, in order to assess how well the class has understood the concept. This process of polling is facilitated by the multiple-choice format of the problem. The time taken to think about and discuss the example helps the students to construct meaning for themselves, which helps their understanding and makes the learning stay with them longer. The active nature of these examples also helps the student maintain their focus and attention during class. When class consists of an instructor simply talking at the students, their attention is more likely to drift, especially during a long class period (Jensen, 1998).

The use of these conceptual examples can also help the students build understanding by forcing them to apply the concepts to new problems and situations. A novice approach to problem solving that is often applied by students is to try to recognize a given problem as being of a type that they have already seen. The students then just solve the new problem in the same manner that they had solved the problem they had seen previously. In this way, a student may be able to get the correct solution without necessarily understanding the fundamental principles they are applying.

[1] http://www.einstruction.com/

Continuing with the concept of mass moment of inertia that was the subject of the conceptual example of Figure 1, we can present a problem that forces the students to apply their understanding of the concept to solve an engineering design problem. For example, consider the satellite shown in Figure 2 where the students are asked to rank the proposed placements of a heavy battery pack from best to worst in terms of minimizing the energy expended for orienting the satellite about its *z*-axis. In this problem the students need to recognize that the kinetic energy of the satellite rotating about the z-axis is equal to $\frac{1}{2}I_{zz}\omega^2$. Therefore, the amount of work that needs to be done to rotate the satellite is minimized when the mass moment of inertia I_{zz} is smallest. Since the mass of the battery is fixed, its contribution to the mass moment of inertia will be smallest when the distance from the *z*-axis is minimized. Therefore, locations *a* and *b* are the best choices for battery pack placement, while location *d* is third best and location *c* is worst.

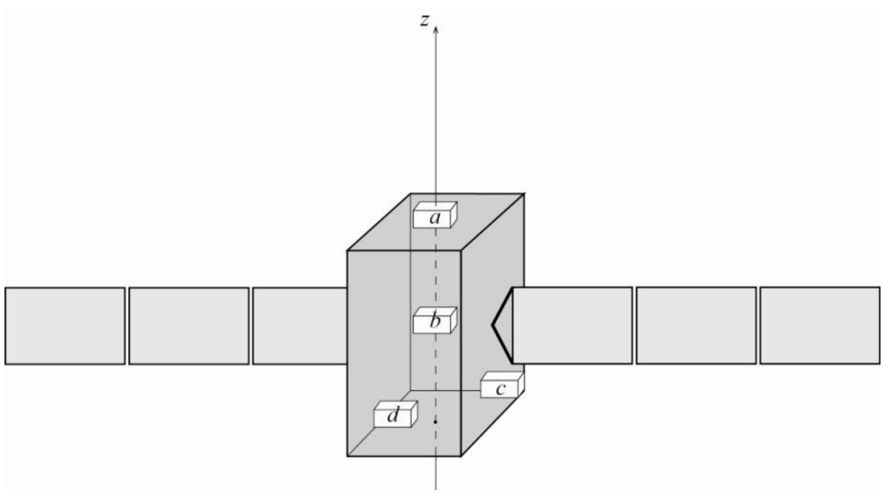


Figure 2 Conceptual example applying understanding of mass moment of inertia

Connecting to the Real World

Often the assignments and assessments in dynamics, and engineering in general, are based on simplified problems that don't accurately reflect the real world and that don't necessarily prepare students to be effective practicing engineers. In dynamics, for example, a typical problem will give precisely the amount of information needed to solve the problem and will explicitly state what assumptions to make. The students do not learn how to make critical decisions about what quantities need to be measured and what types of simplifying assumptions are reasonable for a given analysis.

One way to improve the realism of problems is to provide more information than is necessary thereby forcing students to think critically about what quantities are actually needed. This then relates to the number and types of sensors/measurement devices that are necessary for carrying out a given analysis.

Another way to connect problems to the real world is to have students assess the simplifying assumptions employed in a problem. For example, a student could be asked to solve a problem both with and without air resistance so that they can make an assessment of how large of an effect air resistance has on the results. Even if inclusion of air resistance makes the problem prohibitively difficult to find a closed-form solution for, a student could be asked to predict the qualitative effect of including air resistance. Students could also be provided a simulation that is able to numerically approximate the solution of a problem so that students can see the effect of including the air resistance in their analysis.

Other common simplifying assumptions that can be evaluated are the assumption that a spring is linear (behaves according to Hooke's law) or that friction can be neglected. For example, friction is often neglected in problems so that the principle of conservation of energy can be applied. Similar to the discussion of air resistance above, problems can be solved with and without friction in order to assess whether or not neglecting friction is a reasonable assumption. Alternatively, if the solution of the problem with friction is too difficult, the students can be asked what further information would need to be given in the problem (measured) in order to analyze the problem including the effects of friction.

The modeling of friction in general is a problem of significant practical importance that is often glossed over in a typical undergraduate dynamics course. Specifically, most courses assume a Coulomb-type model where the friction experienced by a body has a magnitude that is exactly equal to the external force applied to the body up until a limit is reached, $F_{f,max} = \mu_s N$, at which point the friction force is modeled as a constant, $F_f = \mu_k N$, where N is the normal force and μ_s and μ_k are the static and kinetic coefficients of friction, respectively. This model is relatively simple, but it doesn't capture the effect of other factors on frictional force, such as the relative velocity between the two contacting surfaces. Ways to address this deficiency include presenting other types of friction models within the course and asking students how their results would differ if these other such models of friction were employed in their analysis. Additionally, you can make students look up various frictional coefficients rather than providing them in the problem. This forces students to consider how the materials involved in a problem affect the frictional forces. Consider the conceptual problem given in Figure 3.

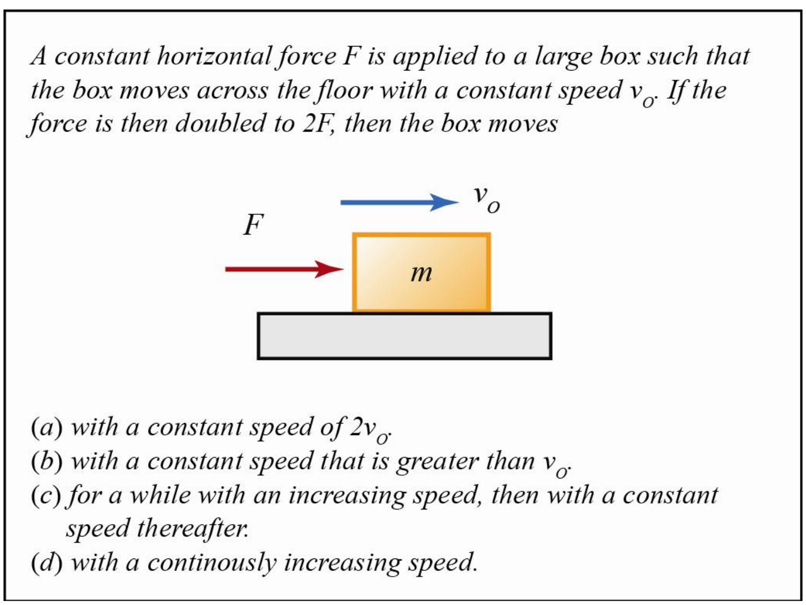


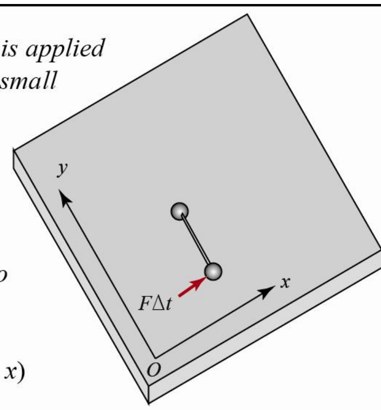
Figure 3 Conceptual example demonstrating the importance of friction modeling

When the box moves with constant speed v_O it is implied that the frictional force F_f and the applied force F balance since the acceleration is zero (by Newton's 2nd Law). If we assume a Coulomb-type model, as is commonly done, then the frictional force $F_f = \mu_k N$ remains unchanged when the applied force is doubled to $2F$. Therefore, since $2F > F_f$ the block will have positive acceleration and its speed will continue to increase indefinitely. This of course makes very little physical sense and provides students the opportunity to consider that the frictional force in reality would also depend on the block's velocity.

Students can also develop a connection between the theory learned in class and the real world by assigning problems and exercises that involve a design component. One example was considered in Figure 2 where the students were asked to determine the best placement of a battery pack on a satellite. Other examples include asking students how to change a physical dimension of a machine (connecting arm, wheel, etc.) to change the resulting magnitude of an object's velocity or acceleration. Not only do problems like these force students to think about a problem in a different way, but they can also motivate and excite students since the students can more directly see the applicability of the theory they are learning to the professions they ultimately plan to enter.

Asking questions that force students to visualize the physical motion produced in a situation is another way to help students build understanding. The motion produced, may be somewhat counter to their intuition. This type of question will strengthen a student's knowledge of the theory being taught. For example, consider the conceptual example depicted in Figure 4. A student's intuition will commonly lead them to assume that the body will move up and to the right in the picture. However, if the students apply the theories relating impulse and momentum that they have learned in class, they will be able to come to the conclusion that the body will translate entirely in the *x*-direction. By helping the students to connect the equations from class to real-world situations, they are more likely to build intuition for themselves and are more likely retain the information they are being presented. This approach is consistent with those instructors who are proponents of using concept inventory tests (Hestenes, Wells, & Swackhammer, 1992) (Gray, Costanzo, Evans, Cornwell, Self, & Lane, 2005).

A large force in the x-direction is applied to the rigid body shown over a small interval of time. Following the removal of the force, how do you expect the rigid body to move?



(*a*) *Translate up (pos y) and to the right (pos x) without rotating.*
(*b*) *Translate to the right (pos x) without rotating.*
(*c*) *Translate up (pos y) and to the right (pos x) while rotating counterclockwise.*
(*d*) *Translate to the right (pos x) while rotating counterclockwise.*

Figure 4 Conceptual example that helps to dispel common misconceptions

Employing Other Learning Modalities

Using videos and animations of a situation being analyzed in class help students build intuition and make a connection to the material. For example, an animation of the problem described in Figure 4 may help some students, those that are visual learners, to better understand the given problem and better retain the underlying theory used to analyze that problem. Simple in-class demonstrations can also help the visual learners in the class. For example, you could take an eraser from the chalk board in the classroom, lay it on a desk, and apply a short impulsive force with your hand and observe the resulting motion. Even better yet, you could take a couple of minutes out of class and have each of the students in the class perform such an experiment at their own desks. This type of experiential learning may be especially helpful to kinesthetic learners. For situations that aren't as easily demonstrated with a simple eraser and your hand, you can also rely on videos of demonstrations of various physical phenomena. The emergence of websites such as www.youtube.com has made these types of clips much more readily available. Another advantage of animations (or videos), as opposed to real-life demonstrations, is that the can be repeated, slowed down, and annotated. For example, a vector could be superimposed on the animation showing how the magnitude and direction of the velocity of a point on a rigid body changes as a given situation evolves.

Implementation

One of the great challenges of the curriculum proposed in this paper is how to fit all of the material into the credit structure of a typical undergraduate dynamics course, as well as how to get students to buy in to the curriculum. The authors first began implementing the techniques outlined here in the winter of 2010 and have collectively taught the introductory dynamics course five times since then, including this current semester. Initial sources for concept-type examples have included (Mazur, 1997) (Gray, Costanzo, Evans, Cornwell, Self, & Lane, 2005). The authors have also been developing their own problems and materials. While issues with development and implementation are still being worked out, the authors will now share some of their preliminary experiences and thoughts.

The use of a great number of conceptual examples and animations/demonstrations within a given lecture and allowing students time to consider and discuss such examples obviously must displace some other aspect of instruction. The authors of this paper have chosen to primarily implement these new activities in place of more calculation-based examples. It is not that that these more detailed type examples aren't useful, it is just that in-class time is better spent on other activities. These displaced examples then must be reviewed by students outside of the typical class period. The authors have found that students are motivated to go through such calculation-based examples on their own if the examples are sufficiently similar to those problems being assigned in the associated weekly homework assignment. The authors have also implemented an extra, hour-long discussion period to go through more detailed examples. Attendance at this discussion section has not been required and has not had points associated with it, but attendance has been highly encouraged, especially for students that are struggling. It has also been standard practice to not simply have the instructor perform the examples, but to rather have select students perform the examples for the rest of the class, where of course the instructor and the other students are available for assistance. One possibility for improving the presentation of such examples by the students is to provide them the examples beforehand in order to prepare their solution. In this manner, the presentation of an example could be done in place of one of the week's assigned problems in order to lessen the workload on the students. These presentations can also cover an activity or experiment, rather than straight, paper and pencil analysis.

An alternative to the approach that has been used here is to displace some of the instructional time as well as some of the more detailed examples. It seems unlikely that some students will, on their own, choose to read the text associated with the course in order to learn the underlying basic theory being omitted from lecture. This differs from what the authors have seen with students going through provided examples on their own time since it requires greater foresight from the students, which is sometimes in short supply, especially in the heat of a semester. One way to force students to do the reading in this case is to use reading quizzes which cover basic concepts from the text. This approach has proved successful in the literature (Mazur, 1997).

Another challenge of this curriculum is that it may be difficult at times to get students to actively participate and give an honest effort. This is especially true if the students' other courses are taught in a more traditional manner and the students have been successful in that paradigm. One way to get students to buy in is to explain what you are doing and why. Also, modifying the assignments and exams of the course to cover concepts rather than just being based on calculations is another way to motivate students to adopt this approach to learning. You can also assign points to in-class activities and participation.

Conclusion

This paper outlines several techniques for improving student understanding and retention of introductory undergraduate dynamics material. These techniques emphasize concepts rather than calculation, try to make problems more realistic, and attempt to involve students more actively in the learning process. While the techniques espoused here have only begun to be developed and implemented, the initial anecdotal evidence has been mostly positive. The authors plan to continue to develop further materials, especially in the form of animations, interactive examples, and activities. Additionally, the authors plan to more rigorously evaluate student performance under this new curriculum. In order to do this, the authors hope to apply these techniques to a larger pool of students, perhaps through collaboration with other, yet unidentified, instructors.

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