Session Number 3668

Development and Assessment of Tutorials for Introductory Engineering Dynamics

Lesley Ann Low*, Paula R.L. Heron, Brian C. Fabien, Per G. Reinhall
Department of Physics, University of Washington/Department of Mechanical Engineering, University of Washington/*currently at Information Systems Laboratories, Inc.

Introductory engineering dynamics is an important course for (at least) three reasons. First, it is essential to have a strong grasp of the concepts covered in the course when pursuing a degree in engineering. Second, it is a required course for most engineering departments and is the first engineering course that covers both difficult and abstract concepts. Third, for many capable students this course can become a roadblock to a career in engineering. This is especially true for the student who has not yet decided if he or she wants to pursue engineering when entering college. For this student the course is often the catalyst for choosing a major that seems less intimidating than engineering. Success in this course is necessary for choosing to, and being able to, enter a department as well as for success in subsequent courses.

Engineering tutorials are being developed at the University of Washington (UW) to respond to the need for increased conceptual understanding and development of problem solving skills early in the engineering student's academic career. Currently, traditional teaching methods are employed in introductory engineering dynamics at UW. The course currently involves three lectures and one recitation section per week during which concepts and examples of their applications are usually presented to the students in a non-interactive environment. Any interaction, if at all, is in the form of students asking questions of the instructor, mostly for clarification. The recitation section, taught by a TA, generally consists of two parts: 1) mini-lecture and 2) question/answer on homework. The mini-lectures cover material that students found difficult on their homework or exams. There are significant differences in student experiences during the recitation sections depending on the teaching assistants (TAs) and their individual teaching styles. There is very little training made available to the TAs and little evaluation of their teaching skills is required.

Research results indicate that very few students develop a conceptual understanding from listening passively to lectures, reading textbooks and working the end of chapter problems[1]. However, providing future engineers with the opportunity to develop conceptual knowledge, reasoning skills and problem solving skills places an increased burden on engineering faculty. It requires them to use instructional methods that were not part of their experiences in the classrooms where they were educated and in which they have typically had no training. There is, therefore, a need for instructional materials that can be adopted with ease and confidence.

In this article we describe a pilot project to address this need by developing engineering tutorials that can serve as supplements to the lectures and the standard textbook and promote active learning by the students. The tutorials were developed in close cooperation with members of the Physics Education Group (PEG) at the University of Washington. With NSF support, the PEG has already developed tutorials used in the instruction of freshman physics[2]. These tutorials address specific conceptual and reasoning difficulties that have been identified through extensive research and teaching experience. The success of the PEG program has achieved national recognition, serving as a model for instruction at numerous colleges and universities. *Tutorials in Introductory Physics* has been adopted in dozens of institutions in the US.

Currently there exists what can best be described as a “culture gap” between physics and engineering that manifests itself in different notations and problem solving techniques and often leads to confusion for students. By working closely with the PEG, the engineering tutorials are able to address this issue and assist in a seamless transition for the students going from physics into engineering.

Methodology

The tutorials developed for use in the instruction of freshman physics by the PEG were used as a model for the engineering tutorials. The main goal of the physics tutorials is to increase student understanding of the concepts of introductory physics. The development of the physics tutorials takes place in an iterative cycle of research, curriculum development and curriculum implementation as described below.

Research on student learning of specific topics indicates the areas of student difficulty that the curriculum must address. This research includes the systematic analysis of student responses to questions administered after lecture instruction on a given topic and often after standard homework exercises have been completed. These questions are often referred to as ‘pretests’ because they precede special tutorial instruction. The results thus provide a baseline for comparisons with post-test results. Interviews with individual students, which allow for in-depth probing of student understanding are often conducted. The pretests also help to inform teaching assistants and other instructors about the nature and prevalence of difficulties students have with specific physics concepts.

‘Pretests’ about specific topics also help students recognize what they do and do not understand and thus help prepare them for the upcoming tutorial. Tutorials are designed to be used in small-group sections (20-24 students) led by specially prepared TA’s. Students work collaboratively in groups of three or four through worksheets that guide them through a series of carefully sequenced activities and questions designed to deepen conceptual understanding and to develop scientific reasoning skills. TA’s ask additional questions intended to help students arrive at the answers themselves.

Most tutorials are conceptual; usually very little calculation is involved. As an example, a tutorial on Newton’s second and third laws asks students to consider two blocks being pushed by a hand across a surface. The students are asked a series of questions intended to help them draw correct free body diagrams for each block and to rank the magnitudes of all the forces exerted on the blocks. This situation is chosen because research reveals that many students initially fail to recognize that the two blocks exert forces on each other that are related by Newton's third law. The questions are posed in a logical way intermixed with activities, such as drawing free body diagrams, so that the students can reach the correct conclusions. Questions are asked throughout the tutorial to see if the student answers are consistent with previous answers and to compel the students to draw conclusions that apply to general situations. Students are significantly more successful when posed related, but not identical problems on post-tests[3].

After the tutorial, the students take post-tests, often as a portion of their physics exams (which also include traditional quantitative physics problems). The post-tests are compared with pretest results (regarding similar concepts) to indicate how well the tutorial addresses the student difficulties. Post-test results can often be compared with results from essentially the same questions given on exams in other academic quarters when the tutorials were not used. The pretest and post-test data along with classroom experience help drive tutorial development. Several accounts of this process have been published[4]. Surveys of student attitudes indicate that most rate the tutorials as very helpful in learning the content.

In this and many other topic areas, the PEG tutorials have been shown to increase student understanding of physics concepts, both at UW and at many other institutions[5]. Although the pretests, tutorial, and post-tests cover conceptual ideas, there is evidence that students often perform better on quantitative questions after working through a tutorial than those students who have not[6]. This success is a driving factor in the implementation of the tutorial process in other fields associated with physics, such as engineering dynamics.

Engineering Tutorials

The development of engineering tutorials is based on the research, curriculum development and implementation model pioneered by the PEG. In a pilot project, tutorials were implemented according to the following sequence: 1) pretests were given prior to tutorials, 2) students worked through tutorials and 3) post-tests were given during engineering exams. The data from the pretests and post-tests are used in the same fashion in engineering as in physics, as described above

The main objective of many engineering classes is to enable the students to solve problems to obtain a quantitative result. This quantitative focus was the greatest difference between the physics tutorials and the engineering tutorials. Conceptual understanding is necessary to be able to obtain a quantitative result. However, the topics covered in engineering dynamics are not new (they are covered in introductory physics), therefore, the engineering tutorial consists of two parts; conceptual and quantitative.

The pretests focused on conceptual ideas important in engineering dynamics and the application of these concepts to quantitative problems. For example, students were asked in one case to identify which formulas they would use to solve a particular problem and why. These types of questions assessed the difficulties students have in applying conceptual understanding to specific problems.

The engineering tutorials are based on typical end-of-the-chapter textbook problem that require many parts to the solution. The first section includes conceptual questions about the situation posed in the problem. These questions ask the students to draw free body diagrams, sketch graphs and consider the general behavior of the system in question. Throughout this section the students are asked if their results are consistent with previous results. A unique aspect of this section is that students are required to compare graphical results to general statements regarding the behavior of the system in question. This type of questioning is intended to help the students develop problem-solving skills.

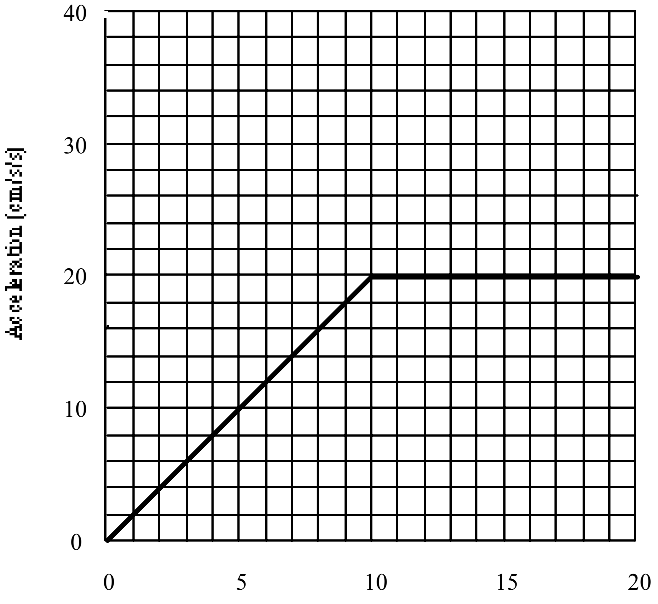
The second section of each tutorial focuses on obtaining a quantitative result for the problem. Students are asked a series of questions that essentially lead them through a series of steps in order to determine the numerical answer. Throughout the second section, the students are asked if their results are consistent with their answers to the conceptual questions posed in the first section. The second section is intended to help the students develop the logical reasoning required to solve engineering problems and to show them the link between the concepts in the first section and how they can be applied, and used to check the quantitative answers.

The final step in the engineering tutorial process was the same as in the physics tutorial process, the post-test. The post-test is a critical step. Ideally it shows whether a tutorial is addressing the difficulties students have with certain topics. During the development of tutorials, however, the post-tests can reveal a great deal of information about different student difficulties.

An example from the pilot study

The engineering dynamics class that used the engineering tutorials consisted of 67 students. Four tutorials were done over the course of the quarter. All of the students worked through the same tutorials, which were implemented in three sections of no more than 27 students. The students worked in groups of 3 or 4, collaboratively, on the tutorial. The results of a sequence consisting of a pretest, tutorial, and post-test on the topic of non-constant acceleration, are presented here as an example.

Pretest



$$v = v_o + at$$

$$v^2 = v_o^2 + 2a(x - x_o)$$

$$x = x_o + v_o t + \frac{1}{2}at^2$$

$$a = \frac{dv}{dt}$$

$$v = \frac{dx}{dt}$$

When answering the following questions assume you know the initial position and velocity of the object.

You are asked to find the distance the object travels during the time interval from 0 to 8 seconds. Which of the formulas (or combination of formulas) listed above will you use? Briefly explain your reasoning.

The pretest question was administered during the first week of instruction at the beginning of the tutorial section. Most students had seen and recalled all of the five formulas listed. However, most students did not retain the fact that the first three equations listed are derived with the assumption that acceleration is constant. This is evident in our study as only 32% of the students answered the question correctly. The overwhelming majority of students stated they would use the formulas for constant acceleration to solve the problem.

Tutorial

The tutorial addresses this issue with the following problem. *A race car starts from rest and accelerates at a = 5 + 2t ft/sec^2 for 10 seconds. The brakes are then applied, and the car has a constant acceleration of –30 ft/sec^2 until it comes to rest. Determine (a) the maximum velocity; (b) the total distance traveled; (c) the total time of travel.*

The students are asked a series of qualitative questions such as: *Sketch a rough graph of acceleration versus time. What quantity is represented by the area under the graph? At what time will the velocity be a maximum*? After answering questions regarding the behavior of the car, the students are led through a series of steps to determine the quantitative result. Throughout the quantitative steps the students are asked if their results are consistent with the qualitative answers such as: *Derive a general equation for* *v(t) during the acceleration phase using a=dv/dt. Is your answer consistent with your graph?*

The first part of the tutorial helps the students gain an understanding of the behavior of the car. They are asked to sketch graphs and from those graphs be able to talk about specific aspects of the car's behavior. This helps the students understand how the problem can be broken into two intervals, the first with changing acceleration and the second with constant acceleration. Knowing when these two intervals occur, the students can apply the appropriate equations to each interval to obtain the quantitative result.

Post-test

The final step in the tutorial process is the post-test that is administered as part of the class exam. Different post-tests were given in each of the three individual tutorial sections. Sections one and three were given questions similar to question 1 and section two was given question 2. The post-test questions are shown below.

1. *An engineer designing a system to control a router for a machining process models it so that the router's acceleration during an interval of time is* $a = -2v\ m/s^2$. *When* $t = 0$, *its position is* $s = 0$ *and its velocity is* $v = 2\ m/s$. *Determine the router's velocity as a function of time.*

2. *Engineers analyzing the motion of a linkage determine that the velocity of an attachment point is given by* $v = A + 4s^2\ ft/s$, *where A is constant. When* $s = 2\ ft$, *its acceleration is measured and determined to be* $a = 320\ ft/s^2$. *What is its velocity when* $s = 2\ ft$?

Because of the nature of the class, the post-test was a typical end-of-chapter textbook problem. Unlike the pretest, students were required not only to use relevant equations, but also to apply them correctly in solving the problem. Thus success on the post-test indicates a higher degree of skill and understanding than did success on the pretest.

Post-test question 1 required operations similar to those outlined in the tutorial, namely integration to determine the formulas for position and velocity. This post-test question was answered correctly by 68% of the students (40 total). However, it could not be answered on the basis of memorization. In contrast, on the pretest the majority of students claimed they could use formulas for constant-acceleration, despite having had instruction on the topic.

Post-test question 2 was significantly different from the tutorial in that differentiation was required. Only 15% of the students (27 total) answered the question correctly. Although most students could recognize the differential and integral relationships between acceleration, velocity, and position, most students did not recognize that when velocity is a function of position (*s*) the velocity must be differentiated to find acceleration.

These data suggest that the tutorial is successful in addressing certain difficulties with non-constant acceleration if integration is required, as was the case in the tutorial. However, continued modification is needed to help students with questions that require greater transfer from the tutorial situation.

Conclusions

The tutorial described above was successful in a case in which the post-test question was very similar to tutorial itself. This result helps to inform the next cycle of development of the engineering tutorial on the topic of non-constant acceleration. By including different types of problems, the students may begin to understand how to apply similar concepts to dissimilar problems.

The engineering tutorials are a work in progress. Most of the published physics tutorials are the result of many iterations. The results from the preliminary versions of the engineering tutorials, including the example given above, are encouraging. With continued research and development we believe the tutorials will be a very valuable tool for helping students deepen their understanding of engineering concepts and improve their problem solving skills.

Acknowledgements

The authors wish to thank Matthew Lautenschlager, Peter S. Shaffer, Lillian C. McDermott, Chad Hislop, and Ian Blanch for their contributions to this project. The support of the National Science Foundation through Grants DUE 9354501 and DUE 9727648 is gratefully acknowledged.

Bibliography

1. *How People Learn*, J.D. Bransford, A.L. Brown, and R.R. Cocking editors, National Research Council, National Academy Press, Washington, D.C., 1999.

2. *Tutorials in Introductory Physics*, L.C. McDermott, P.S. Shaffer, and the Physics Education Group at the University of Washington, Prentice Hall, Upper Saddle River, NJ, First Edition, 2002.

3. L.C. McDermott, P.S. Shaffer and M.D. Somers, "Research as a guide for teaching introductory mechanics: An illustration in the context of the Atwood's machine," *Am. J. Phys.* **62** (1) 46 (1994).

4. See for example, P.R.L. Heron, M.E. Loverude, P.S. Shaffer, and L.C. McDermott, "Helping students develop an understanding of Archimedes' principle: Research on student understanding, Part II: Development of research-based instructional materials," *Am. J. Phys.***71** (11) 1188 (2003), K. Wosilait, P.R.L. Heron, P.S. Shaffer, and L.C. McDermott, "Development and assessment of a research-based tutorial on light and shadow," *Am. J. Phys.* **66** (10) 906 (1998).

5. See, for example, G.E. Francis, J.P. Adams, and E.J. Noonan, "Do they stay fixed?" *Phys. Teach.* **36** (8), 488-490, 1998; E.F. Redish and R.N. Steinberg, "Teaching physics: Figuring out what works," *Phys.*

Today, **52** (1) 23-40 (1999); E.F. Redish, “Building a science of teaching physics - Millikan lecture 1998,” *Am. J. Phys.* **67** 562-573 (1999).

6. See, for example, B.S. Ambrose, P.S. Shaffer, R.N. Steinberg, and L.C. McDermott, “An investigation of student understanding of single-slit diffraction and double-slit interference,” *Am. J. Phys.* **67** (2) 146–155 (1999).

LESLEY ANN LOW received a Ph.D. in mechanical engineering from the University of Washington in 2002 and was a post-doctoral research associate in the Physics Education Group at the University of Washington. Currently a research scientist at Information Systems Laboratories, Inc. in Seattle, WA, her research interests are in nonlinear dynamics.

PAULA R.L. HERON is an Associate Professor of Physics at the University of Washington, where she is a member of the Physics Education Group. She has published several papers on her research on the learning and teaching of physics. Dr. Heron is currently a member of the Executive Committee of the APS Forum on Education. She consults on several NSF-funded education projects.

BRIAN C. FABIEN is currently a Professor in the Department on Mechanical Engineering at the University of Washington. His research interests include the kinematics of mechanisms, dynamic system analysis and optimization, as well as control system design.

PER G. REINHALL a Professor in the Department of Mechanical Engineering at the University of Washington and his main research interests are in the areas of nonlinear dynamics and structural acoustics. He is also involved in system identification, stochastic processes, and computational methods applied to elasticity and plasticity.