Research-based Modifications to Instruction in Physics Courses for Engineers

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In the last few decades, research into the teaching and learning of physics has resulted in course modifications that produce measurable improvement in students' conceptual understanding. These instructional modifications often necessitate reduced focus on problem-solving instruction. An important question, therefore, is how these instructional modifications affect students' problem-solving ability. In this paper, I will discuss some of the research that underlies changes to physics instruction. Measures of the effectiveness of these modifications on conceptual understanding, problem-solving ability, and student performance in subsequent engineering courses will be described. Examples will be given in the context of electric circuits, electrostatics, and mechanics.

Introduction

Most physicists believe that their education has provided them with problem-solving skills that can be applied to problems outside of physics. The physics community has increasingly turned these skills to problems in physics education. Why is physics hard? What do students learn as a result of physics instruction? What can be done to improve students' understanding of physics?

For a variety of topics, physics education researchers have found that students come into physics with misconceptions about the physical universe that are strongly held {1}. Many students learn to solve standard physics problems and do well in physics courses without altering these original ideas about underlying concepts. By asking conceptual questions (usually first in one-on-one interviews with students and later with larger groups of students) physics education researchers have been able to identify common conceptual difficulties, to establish the prevalence of these difficulties, and to develop instructional strategies that are effective in addressing these difficulties. There is an ongoing effort to identify conceptual difficulties that are topic-specific and to develop curricula that effectively address these difficulties.

As more of these difficulties are identified, some common threads are emerging. For example, research into student difficulties with kinematics has shown that in some contexts many students fail to differentiate between position and velocity or between velocity and acceleration. Investigation into student understanding of Faraday's law reveals that students commonly use flux rather than change in flux to predict the emf in a loop. In these and other topics, many students fail to differentiate between a quantity and the time-rate-of-change of that quantity.

This paper describes portions of an ongoing investigation into the connection between conceptual knowledge and problem-solving ability in physics {2}. To what degree do students apply conceptual knowledge to the solution of traditional examination and end-of chapter physics problems? Are there instructional strategies that can facilitate this application? How do the identification of these difficulties and the development of research-based curricula benefit engineering students? Are students more successful in their engineering studies as a result of research-based physics curricula? More specifically, is improved problem-solving ability an outcome of curriculum that has been designed to improve conceptual understanding? These

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questions are especially important to ask in situations where implementation of curriculum to address students' conceptual difficulties is at the expense of time that could be used in problem-solving practice.

Conceptual difficulties: An example from electric circuits

Two common student beliefs about electric circuits that have been identified by physics education researchers are (a) current is 'used up' by resistive elements (i.e., the current leaving these elements is less than the current entering these elements) and (b) a battery acts as a constant current source. For many students these ideas about electric circuits persist after instruction {3}. The prevalence of these difficulties after instruction is suggested by examining student responses to the 'five bulbs' question shown in Figure 1. This question has been asked of over one thousand students in introductory physics courses, both before and after instruction. The prevalence of common responses does not vary significantly from instructor to instructor or from university to university. More alarmingly, the success rate of students at this task is relatively independent of whether the question is asked before or after instruction.

The three circuits at right contain identical bulbs and identical batteries. Assume the batteries are ideal (i.e., the batteries have no internal resistance).

Rank the brightness of the five bulbs. Explain how you determined your ranking.

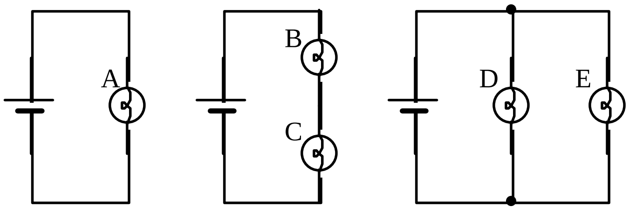

Figure 1. 'Five bulbs' question

A correct response is that since the bulbs A, D, and E all have the same electric potential difference across them, they will have the same brightness. Bulbs B and C each have half the electric potential difference across them, and so they will be the same brightness, but will be less bright than bulbs A, D, and E.

After traditional physics instruction, approximately 20% of students in a calculus-based introductory course can answer this question correctly. About one-quarter of all students will give a ranking that includes B > C. Their reasoning consistently suggests a belief that current is used up by bulb B:

> ". . . C receives the leftover current from B."

An additional one-quarter of the students responding gave the two most common incorrect rankings, A > D = E > B = C and A = B = C > D = E. Reasoning for the first of these responses varied, but often included a mixture of reasoning about series and parallel circuits and about voltage. Reasoning for the second response usually indicates a belief that a battery acts as a constant current source:

> "Current is equal for the first 3 but is split through the system in parallel."

The 'five bulbs' question has also been asked of high school physics teachers and of university faculty in science fields other than physics. In both cases about 15% answer correctly. About 70% of physics graduate students answer correctly. This suggests that the underlying concepts are difficult for most students, and that the conceptual difficulties are often not addressed by subsequent and more mathematically sophisticated treatment of the material.

Addressing conceptual difficulties

A wide variety of instructional strategies that are based on physics education research have been developed and tested. Effective curricula share some common features {4}. Students must become actively involved in some manner; it is not sufficient just to explain clearly that a particular error should be avoided. Examples of active student involvement include interactive lectures, guided group inquiry, and microprocessor-based labs. It is helpful if the curriculum elicits known student difficulties so that they can be discussed and examined. A physical situation in which elicited misconceptions lead to a prediction that is incorrect upon testing is very valuable. Finally, it is helpful for students to learn and practice with a physics model that does lead to correct predictions. Physics education researchers did not invent these instructional strategies. Skilled instructors often employ them as a matter of course, and they are consistent with ‘best practices’ advocated by education researchers in other fields.

For many topics in physics, instructional strategies and curricula have been developed that have resulted in significant improvement in students’ conceptual understanding. For example, the curriculum developed by the Physics Education Group at the University of Washington as part of *Physics by Inquiry* and *Tutorials in Introductory Physics* {5} has been demonstrably effective in assisting students in developing a conceptual model for current in circuits. Students, working in groups of 3-4 with simple materials, are guided through a series of research-based activities during a weekly 50-minute tutorial. As part of this experience, students develop a qualitative model that allows them to reason about current in electric circuits.

Are students who have developed this conceptual model then better at solving a quantitative problem involving current in electric circuits? Paired qualitative and quantitative questions

Effect of conceptual development on problem solving

To test whether students who demonstrate that they have developed a conceptual model for electric circuits are better able to solve quantitative circuits problems, two questions were asked on a midterm examination in two different sections of a calculus-based physics class at the University of Washington. Students had completed all instruction in electric circuits at the time of the midterm examination, and had also completed a laboratory on electric circuits and the tutorial materials on electric circuits. As part of a series of questions on the first page of the examination, students were asked to rank the currents through the four bulbs in the circuit shown in Figure 2.

The circuit at right contains four identical light bulbs and a battery.

Rank the brightnesses of the four bulbs. Explain how you determined your ranking.

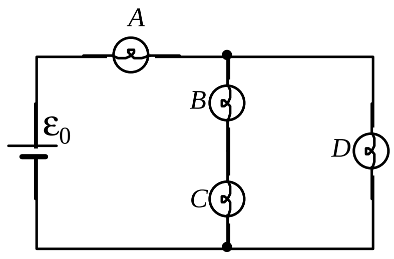

Figure 2. Paired circuits examination question -- qualitative

A correct response requires that students recognize that the current will split at the junction after bulb A and that there will be more current in the branch with the least resistance (the branch containing bulb D). Students must also relate the brightness of identical bulbs to the current through them. Below is a correct response from a student:

> “A > D > B = C. A is in series with the power supply but D is in parallel with B & C. Since the current splits it is higher for A than the rest. D has less resistance than B & C combined so more current will flow through it.”

This is an example of reasoning based on the model developed in the tutorial on electric circuits.

As part of a series of questions on the third page of the same examination, students were asked to express the current through each resistor in terms of the current through the battery for the circuit shown in Figure 3.

Resistors R_A, R_B, R_C, and R_D all have the same resistance R. Assume the batteries are ideal.

Let i_o be the current in the battery. Find the current in each resistor in terms of i_o. Explain your reasoning or perform a calculation that clearly demonstrates how you arrived at your answer.

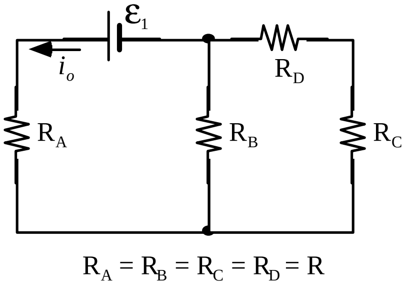

Figure 3. Paired circuits examination question -- quantitative

This second question requires that students extend the model developed in tutorial to a quantitative analysis. The following student quote is an example of this extension:

> “$i_A = i_o$ $i_B = 2/3i_o$ $i_C = i_D = 1/3i_o$. The current i_o is the same thru R_A, splits and is greater thru R_B than thru R_D and R_C. 2x the current goes thru R_B because it has 1/2 the resistance.”

The results from the two classes were similar and have been combined in Figure 4. Each shaded square represents a single student. One indication of the success of the tutorial approach is that two-thirds were able to rank the bulb brightness with correct (although sometimes incomplete) reasoning. Only one student who could not do the ranking task could calculate the current (lower right quadrant). Only about one-quarter were also able to answer the related quantitative question (upper right quadrant).

About 40% of the students were able to answer the qualitative question but were unable to answer the quantitative question (upper left quadrant).

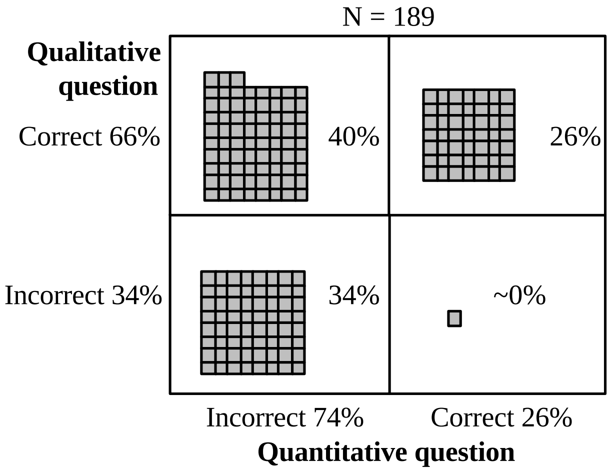

Figure 4. Correlation of performance on qualitative and quantitative questions – post tutorial

This result is consistent with results reported by other researchers who have investigated student performance on quantitative physics questions after curriculum has been implemented that focuses on conceptual development. Even in cases where less time is spent on problem-solving as a result of modifications to the curriculum, students do slightly better on quantitative problems.

Why only slightly better? A closer look at student solutions to the two questions suggests an answer. Many of these students did not approach the quantitative question in the same manner in which they approached the qualitative question. A common pair of responses was a correct qualitative response to the bulb circuit (Figure 2) and an equation-driven response to the quantitative question (Figure 3) that seemed to have no direction and included no written description. This result was consistent with analysis of interview responses that suggested that many students did not make a strong connection between the concepts developed in tutorials and the traditional problems they were being asked to solve in homework and on examinations.

Making a stronger link between concepts and problem solving

We designed a series of homework worksheets intended to more strongly link concepts and traditional problems. These worksheets, which we called 'bridging exercises' typically started with conceptual questions that were very similar to questions asked in the tutorials, and then progressed to more quantitative analysis of standard problems. Where possible, we based the questions that we asked on the worksheets on known conceptual and procedural difficulties.

To measure the effectiveness of these exercises, we again asked the paired conceptual and traditional questions shown in Figures 3 and 4 in two sections of the calculus-based course with different instructors. Results are shown in Figure 5. Over half of the students could now answer both questions correctly. Additionally, it appears that the additional reinforcement provided on the homework has served to improve students' conceptual understanding.

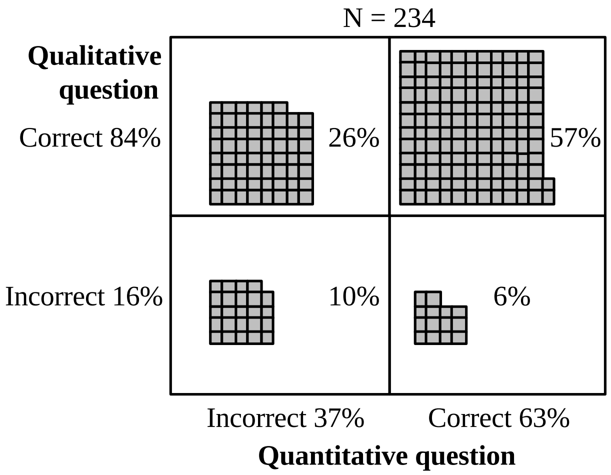

Figure 5. Correlation of performance on qualitative and quantitative questions – post tutorial and 'bridging exercises'

The bridging exercises were not as successful in areas where students' conceptual difficulties are not as well understood as electric circuits. In some areas such as electrostatics, poor performance on the bridging exercise homework led to additional research into students' conceptual difficulties. This research led in turn to modifications to the tutorials and to the bridging exercises.

Effect of research-based instruction on subsequent coursework

Some of the introductory physics courses for engineers at New Mexico State University have in the past few years been conducted with an increased emphasis on conceptual understanding as part of the lecture. Homework assignments for these pilot courses have been modified to include some problems that serve as bridging exercises. We have been monitoring the progress of students in these courses as they complete subsequent engineering coursework. Although the numbers are small, preliminary results are encouraging. For example, of 21 students who completed Engineering Statics after completing a pilot Physics 215 (Mechanics) course, 14 received A's. Thirteen of these students received higher grades in their engineering course than they did in their physics course, and only one received a lower grade (the distribution of grades is similar in the two courses. We will continue to monitor the effectiveness of the modifications that are made to physics courses in this manner.

Acknowledgements

The author would like to thank the many students who participated in the studies described in this paper. The assistance of all members of the Physics Education Group at the University of Washington is gratefully acknowledged. Finally, the New Mexico State University Physics Department has been very supportive of this research and of implementation of improvements to curriculum.

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Biography

Stephen Kanim received his B.S. degree in electrical engineering from the University of California at Los Angeles in 1981 and worked as an engineer until 1987. He received a secondary teaching credential from San Jose State University in 1987 and taught physics in public high schools from 1987 to 1992. He received a Ph.D. in physics from the University of Washington in 1999. He is an assistant professor in the physics department at New Mexico State University. His research interests are in the teaching and learning of physics.