Student Understanding of Circuit Loading in Physics and Engineering

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Abstract: As part of a new effort to investigate the learning and teaching of concepts in thermodynamics and electronics that are integral to both undergraduate physics and engineering programs, we have been examining student learning in electrical engineering and physics courses on circuits and electronics. Due to the considerable overlap in the content coverage, we have been able to administer the same (or similar) questions to students in both disciplines. A major goal of this work is to investigate the impact of disciplinary context on the nature of student understanding, including the prevalence of specific difficulties. This paper focuses on foundational concepts of circuit loading that are critical to the design and analysis of circuits covered in both courses investigated. In this preliminary investigation, we find that between one-quarter and one-third of students in both disciplines still struggle with basic concepts of voltage division and loading after electronics instruction.

Keywords: analog electronics, student understanding, circuit loading, electrical engineering.

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INTRODUCTION

Physics education research (PER) has a rich history of over 30 years of investigations of student understanding and performance on a multitude of topics in a wide variety of contexts, and has produced many seminal results [1]. Engineering education research (EER) is a more recently established, albeit rapidly growing, field that began in the mid 1990s around the time of key changes in the ABET accreditation. (See [2] and [3] for a more complete history.) From its inception, EER has focused mostly on non-introductory topics, whereas PER has only recently begun to explore upper-division topics.

Thus far, EER and PER studies of topics that cross disciplines have been performed independently, with the work in one field often not building upon work in the other. Moreover, instructional materials and research instruments developed in one field are rarely used in the other. There is a growing recognition, however, that researchers in engineering education and physics education could benefit from increased collaboration, and a few notable efforts have been made. In particular, an article co-authored by a leading PER researcher, in a special 2008 edition of the *Journal of Engineering Education*, provided a survey of current physics education research relevant to engineers [4]. To date, however, there have been no systematic efforts to study student understanding (including the prevalence of specific difficulties) and learning across the disciplines.

At the University of Maine, we have recently received a grant from the National Science Foundation to investigate the learning and teaching of thermodynamics and electronics in both physics and engineering courses. In our work on analog electronics, we have been exploring student understanding of both foundational circuits concepts (*e.g.,* Kirchhoff's rules, voltage division, and loading) and circuits containing canonical elements in electronics (*e.g.,* diodes, bipolar-junction transistors, and operational amplifiers). Many of these topics are covered (*i.e.,* introduced, revisited, or applied) in multiple electrical engineering courses, and a small number of EER papers on devices such as operational amplifiers [5] and transistors [6].

Voltage division is a particularly ubiquitous and foundational concept in analog electronics. The most basic voltage divider circuit consists of two resistors in series and may be used to produce an output voltage (V_{out}) that is a fraction of the circuit's input voltage (V_{in}). In practice, most circuits or circuit fragments can be treated as voltage dividers, and most practical circuits consist of many circuit fragments. Thus, students need to be able to determine the extent to which the addition of a second circuit fragment "loads" the original divider, thereby impacting V_{out}. The simplest case, sometimes discussed in introductory physics, is the addition of a single load resistor to the voltage divider shown in Fig. 1.

Several investigations of student understanding of introductory circuits have discussed the concepts of equivalent resistance and voltage in simple DC

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circuits [7,8]. However, to the best of our knowledge, we are aware of no previous studies of circuit loading, particularly in upper-division physics and engineering courses on analog electronics.

In this paper, we describe preliminary results from an ongoing investigation of student understanding of circuit loading in junior-level electronics courses in physics and engineering. Due to the relatively small number of students involved thus far, we will focus primarily on general trends in student performance and key difficulties related to circuit loading, thereby contributing to the existing research base on circuits and electronics. In addition, we hope to demonstrate the utility and value of conducting such investigations across disciplines, and to show how this approach opens up new possibilities for research.

CONTEXT FOR RESEARCH

This study was conducted in the context of two junior-level courses, one in physics and one in electrical engineering, at the University of Maine. The physics course focuses on analog electronics and is required for all physics majors. The course, for which the introductory calculus-based physics sequence is the sole prerequisite, begins with a treatment of voltage division and equivalent circuits, moves into ac circuits, and then covers diode, transistor, and op-amp circuits. One-hour lectures are held twice a week, and there is a weekly two-hour lab session. During this study, 18 students were enrolled in the course.

The electrical engineering course, required for all electrical and computer engineering majors, focuses on analog electronics and semiconductor devices. The course begins with a treatment of non-idealized operational amplifiers, and then covers diode and transistor circuits. More basic topics such as voltage division, equivalent circuits, and ac circuits are all covered in earlier required electrical engineering courses. One-hour lectures are held three times a week, and there is a weekly three-hour tutorial session and a weekly two-hour lab session. (In practice, students are expected to spend additional time in the lab working on designs and completing their experiments.) During this study, 36 students were enrolled in the electrical engineering course. A single student was enrolled in both courses, and has been omitted from the data presented.

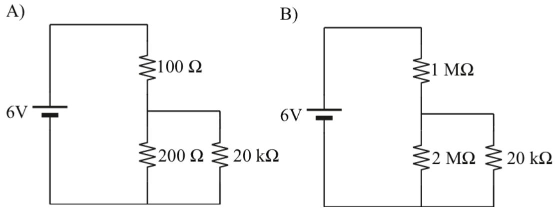

FIGURE 1. Circuits for comparison in Loading Task 1.

OVERVIEW: LOADING TASKS

For this study, a sequence of two questions on circuit loading was administered in both courses during the first and final weeks of class. The questions were ungraded, although participation credit was awarded in the physics course. Students were told to assume that all circuit components in both questions are ideal.

In the first question, Loading Task 1, students were shown two "loaded" voltage divider circuits consisting only of batteries and resistors (Figure 1). Students were asked if the absolute value of the voltage across the 20 kΩ resistor in circuit A was greater than, less than, or equal to the voltage across the 20 kΩ resistor in circuit B, and to explain their reasoning. The correct answer is $V_A > V_B$; even though the leftmost resistors in each circuit form a 1:2 voltage divider, the addition of the 20 kΩ resistor to circuit B loads the circuit substantially (*i.e.,* decreases the resistance of the lower portion of the divider chain), and thus the voltage in the lower portion decreases.

In the second question, Loading Task 2, students were presented with four voltage divider circuits loaded with a variety of different elements (Figure 2). Students were asked to rank, from largest to smallest, the absolute values of the voltages across the 20 kΩ resistors in the four circuits A-D, to state explicitly if any voltages were zero, and to explain their reasoning. Additionally, students were instructed to omit a circuit from their ranking if they were unsure of how to analyze that circuit.

On this task, a correct response would be that $V_A > V_B = V_C = V_D = 0$. In circuit C, the diode is oriented such that it is back-biased, and will thus have a negligible current through it. In practice, this usually is treated as exactly zero, but students who indicated the current was small were counted as correct. In circuit D, there will be no current through the open switch, and hence the current through and voltage across the 20 kΩ resistor will be zero. Effectively, circuit D is not loaded, so the voltage across the switch will be 4 V, equal to that across the 200 Ω resistor via

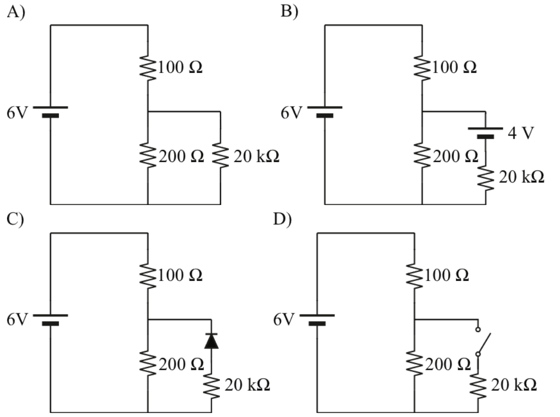

FIGURE 2. Circuits for comparison in Loading Task 2.

Kirchhoff's loop rule. As circuit B already has 4 V dropped across the added battery, then it follows that there must be no current through it and therefore no voltage across the 20 kΩ resistor, as Kirchhoff's laws have a unique solution.

These two questions were paired to probe circuit loading in complementary ways. Loading Task 1 focuses on the impact of loading on output voltage, whereas Loading Task 2 focuses more on the currents drawn through various loads, with the voltage across the 20 kΩ resistor serving as a proxy for the current through the load branch.

RESULTS: LOADING TASK 1

Loading Task 1, pretest. On the pretest, approximately 60% of the students in the physics and engineering courses correctly indicated that $V_A > V_B$, as shown in Table 1. Roughly 40% all students provided correct answers supported by correct and complete or nearly complete reasoning.

Roughly one quarter of all students stated that $V_A = V_B$, and the supporting explanations were typically similar. As one student noted, *"[B]ased on voltage division, we know the proportions are the same, so the voltages are same."* Indeed, 88% (N=8) of those students who indicated that $V_A = V_B$ focused on the fact that the ratio of the leftmost resistors (*i.e.,* those in the unloaded voltage divider) was the same. Thus, 25% of all students (19% in physics and 31% in engineering) failed to recognize that the addition of the load *can* impact the voltage division and that the resistance of the load must be compared to the resistances in the divider chain to ascertain the load's potential for impacting the voltage division.

Less than a quarter of all students incorrectly claimed that $V_A < V_B$. Of these students, 60% (N=5) only compared the resistors in the parallel branches of each circuit. For example, one student wrote, *"I always thought the current took the path of least resistance. So, in A we have two paths, one 200 Ω, the other 20 × 10^3 Ω, so more would travel on the 200 Ω side. But, on B we have 2 × 10^6 Ω and 20 × 10^3 Ω, so more goes through the kΩ side. So, B has more net voltage across the 20 × 10^3 Ω side than A."*

Here, the student began by comparing the resistance of each of the 20 kΩ resistors with that of the resistor in parallel with it. The student then correctly argued that less of the total current in circuit A will pass through the 20 kΩ resistor, whereas more of the total current in circuit B will pass through the 20 kΩ resistor. Students using this approach failed to recognize that the total currents in circuits A and B will not be the same. Such reasoning was given by 13% of all students (19% in physics and 6% in engineering).

Loading Task 1, post-test. The physics course showed some improvement in its post-test responses, whereas the percentage of correct responses in the engineering course was essentially the same. (See Table 1.) Overall, only approximately 70% of all students gave correct comparisons after all electronics instruction; this result is somewhat surprising given the fact that the concepts tested are viewed as foundational for the majority of topics covered in both courses. Due to some students not being present for the post-assessment, we have only reported matched data. We note, however, that the use of matched data changed the post-test results very little.

	Pre		Post	
	PHY (N=16)	ENG (N=16)	PHY (N=16)	ENG (N=16)
$V_A > V_B$ (Correct)	56%	63%	75%	69%
$V_A = V_B$	19%	31%	6%	19%
$V_A < V_B$	25%	6%	19%	12%

TABLE 1. Matched data for answers on Loading Task 1.

Our data suggest that there may be a correlation between course/discipline and the most prevalent incorrect answer (and associated reasoning). Although not statistically significant on the basis of this data set, the $V_A = V_B$ response is the most prevalent incorrect response given by the engineering students, whereas the $V_A < V_B$ response is the most prevalent incorrect response given by the physics students. We anticipate that additional data will help provide the statistical power needed to determine the extent to which this observed difference really exists. It is important to note, however, that the two most prevalent incorrect responses were observed in both populations.

RESULTS: LOADING TASK 2

Student performance on Loading Task 2 was poor in general. Indeed, 0% and 12% of physics and engineering students, respectively, on the pretest, and 19% and 0% of physics and engineering students, respectively, on the post-test gave completely correct rankings. No student offered correct and complete reasoning. We found that almost all students struggled with circuit B, which is consistent with published findings from research on student difficulties with multiple-battery circuits [9,10]. Thus, for the purpose of clarity, we omit circuit B from our discussion and we focus on comparisons between circuits A and C and circuits A and D. When developing Loading Task 2, we hypothesized that student performance on the A/C and A/D comparisons should be similar provided students have developed a robust understanding of diode circuits. Indeed, a reverse-biased diode (as in circuit C) may be thought of as an open switch. Thus, if a load contains either circuit element, there will be no current through the load and the output voltage will remain unchanged.

On the pretest A/C comparison, we found that 63% of physics students explicitly stated that they did not know how to analyze the diode circuit, while fewer (11%) of the engineering students stated the same thing. It is worth noting that diodes are not covered in the calculus-based introductory physics course, but engineering students encounter diodes briefly in a laboratory experiment in a prerequisite course.

On the post-test A/C comparison, we found that the majority of students in both courses ranked V_A as greater than V_C, although many students did not explicitly indicate that $V_C = 0$. While many of these students did not explain their reasoning, some students offered detailed explanations. For example, one student wrote, *"A drops about two thirds of the voltage, while C drops that two thirds minus about 0.7 V due to the reverse bias diode."* We found several other instances of students ascribing a forward-biased voltage drop of 0.7 V to a reverse-biased diode. While not particularly prevalent on this task, it has been identified in investigations of introductory and upper-division student understanding of diode circuits [11].

For both populations, pretest performance on the A/D (open switch) comparison was considerably better than that on the A/C (reverse-biased diode) comparison, suggesting that most students enter these courses without a robust understanding of diodes. On the post-test, the performance of each population on the A/D comparison is quite similar to that on the A/C comparison, suggesting a more solid understanding of diodes circuits. (As before, additional data are needed to increase statistical power to explore that claim more thoroughly.) Approximately one-third of the students in these courses, however, are still unable to answer either comparison correctly after instruction.

DISCUSSION

Approximately one-quarter to one-third of each population could not properly compare the very basic circuits in Loading Task 1, and largely similar performance was observed on the somewhat more challenging Loading Task 2. It is important to note, however, that our analysis of Loading Task 1 indicated that many students demonstrated productive ideas and approaches that could contribute to a complete and correct analysis of the problem.

In addition, we were initially surprised by the fact that we found little to no evidence of improvement on these tasks in the engineering course. However, our findings make more sense when one recognizes that the course itself emphasizes in-depth, formal mathematical analyses of semiconductor devices and the associated circuits, so concepts such as voltage division and loading are not foregrounded to the same extent as they are in the physics course.

CONCLUSION

Preliminary results from this study suggest that a significant percentage of students who complete an upper-division electronics course in either physics or electrical engineering still struggle with the foundational concepts of voltage division and loading. We have identified two common incorrect lines of reasoning used by students in both populations when analyzing circuits with loads, and our findings also suggest that the relative prevalence of these incorrect explanations may, in fact, be discipline dependent. We plan to collect additional student data on the existing tasks and to develop new tasks and related interview protocols in order to gain greater insight into student understanding of circuit loading. These efforts will also be used to guide the ongoing development of research-based instructional materials on this topic.

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