Substituting Traditional Hands-On Laboratories with Computer Simulations: What's gained and what's lost?

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Introduction

Most introductory physics courses contain some sort of laboratory section, and this is often the only segment of a course that allows students to be directly engaged with the content and observe physics “in-action.” Instructors have numerous goals and expectations for their students to achieve by completing these labs, which include, but are not limited to, confirmation, developing mechanical skills, error analysis, empiricism, and concept building. Occasionally, laboratory curricula have attempted to provide students with an environment that, to some extent, resembles a research scientist. If one were to instead replace this environment with a computer simulation that replicates physics concepts, what would happen?

As one may expect, there may not be a global answer to this question—it may depend on the subject matter at hand, the environment in which a simulation is introduced, the characteristics of the user, and the goals that an instructor has in mind. To narrow down the focus, this study will look at how one particular computer simulation, known as the Circuit Construction Kit (CCK), affected Physics 1120 students’ conceptual understanding of DC circuits, compared to their classmates who used real equipment. There is reason to believe that CCK is better at helping students develop intuitive knowledge about current flow, since the flow of electrons is explicitly shown in the simulation. Thus far, the results from this study show that students who used CCK performed slightly better than students who used real equipment when answering multiple choice questions on a course examination.

Background

Computers have been used in classrooms for quite some time now. Their function has been to supplement large lectures and acquire data and display those data in real-time. [1,2,3,4,5,6] We do find a few studies that look at replacing hands-on labs with computer simulations.[7,8,9,10]

The focus of this study is similar to that Finkelstein, *et al.*, where CCK was introduced into a different university environment and was shown to be more successful at developing conceptual understanding than a traditional laboratory.

The simulation used in this study was develop and tested by the Physics Education Technology (PhET) group at the University of Colorado at Boulder. They have developed a variety of physics simulations that include most of the topics covered in a typical introductory physics sequence. The simulations are also downloadable for free online.[11] These simulations are designed to be interactive, engaging, and explicitly show various phenomenon.[12]

The simulation used in this study, the Circuit Construction Kit, allows students to build simple DC circuits with batteries, wires, resistors, light bulbs, and switches. The simulation utilizes Kirkoff's law to accurately model current and voltage for a given circuit. A workplace is provided where students can place various components, connect them together, and measure various properties with a virtual amp meter and volt meter. In addition, a key distinction between real circuits and their virtual counterparts is that CCK explicitly shows students the manner in which electrons flow through a circuit. Students can see the way in which current splits and recombines at various points along the circuit. This feature, of course, is not made available for students who use real batteries, bulbs, and wires.

This study was conducted in the Fall 2004 semester in Physics 1120, the second semester of a calculus-based, introductory physics sequence intended for engineering, chemistry, and physics majors. In addition to lecture, students meet weekly for a one hour recitation section, where they work on tutorials from *Tutorials in Introductory Physics*.[13] Among other topics, the students completed two different DC circuit tutorials, one on current and resistance and another on voltage (p. 97-106). Half of the recitations used real equipment to complete the tutorials, and the other half used CCK in place of real equipment. The tutorials that the CCK students used were only slightly modified from the original version to make certain instructions clearer; the questions and tasks were left unchanged.

Data

Recall that the focus of this study is to see how CCK affected students' conceptual understanding of DC circuits. Thus, verification is necessary that the experimental group (CCK) and the control group (Real) both have the same understanding of DC circuits prior to any intervention. Before the students received any instruction, the Brief Electricity and Magnetism Assessment (BEMA) exam was given to the entire course. The BEMA exam is a 31 question, multiple choice assessment survey covering most topics found in a typical second semester introductory physics course.[14] Three additional questions on DC circuits were added to the exam. All 6 questions on the BEMA exam relating to DC circuits were analyzed. There are no statistically significant differences between the two groups on any of the questions (see figure 1).

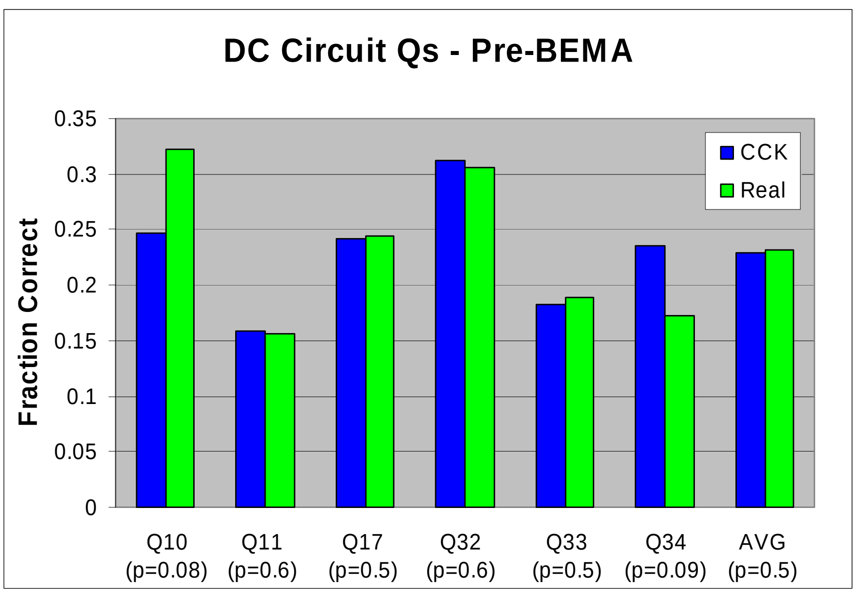

Figure 1 - Fraction correct of six questions on the BEMA exam relating to DC circuits. All p-values were obtained with the Fischer Test. No question yields a statistically significant difference.

During the two tutorials where CCK was used, observations were taken to determine how students were using CCK and to look for common problems students were having when using the simulation. Most students found the simulation fairly easy to use; some problems were encountered at first, but these were usually solved by one of the group members after some trial and error. Occasionally a computer would crash or freeze up, but these only caused minor delays and were not a major inconvenience for the students. It was also noted that some groups of students were observed “playing” with the simulation, trying to catch batteries on fire and building odd circuits. Sometimes this occurred after the students had finished the tutorial, but occasionally students would play with the simulation prior to the start of tutorial.

An exam was given four weeks after the second circuits tutorial; the exam consisted of 15 multiple choice questions and two long answer questions that required students to give an answer and explain their solution. Six of the 15 multiple choice questions were directly related to DC circuits, and the other 9 multiple choice questions were on other topics. All the multiple choice questions were analyzed to look for differences in performance among the experimental and control groups.

In figure 2, we can see the how both groups performed on the 9 questions on topics unrelated to DC circuits. None of the questions yield a statistically significant difference between the two groups. The average of all 9 questions yields a p-value of $p=0.4$ using the Fischer Test.

In figure 3, we can see the performance of each group on the remaining 6 questions relating to DC circuits. Questions 8 and 13 are statistically different, and their p-values are $p=0.02$ and $p=0.04$, respectively. The average of all 6 questions is also statistically significant ($p=3\times10^{-6}$).

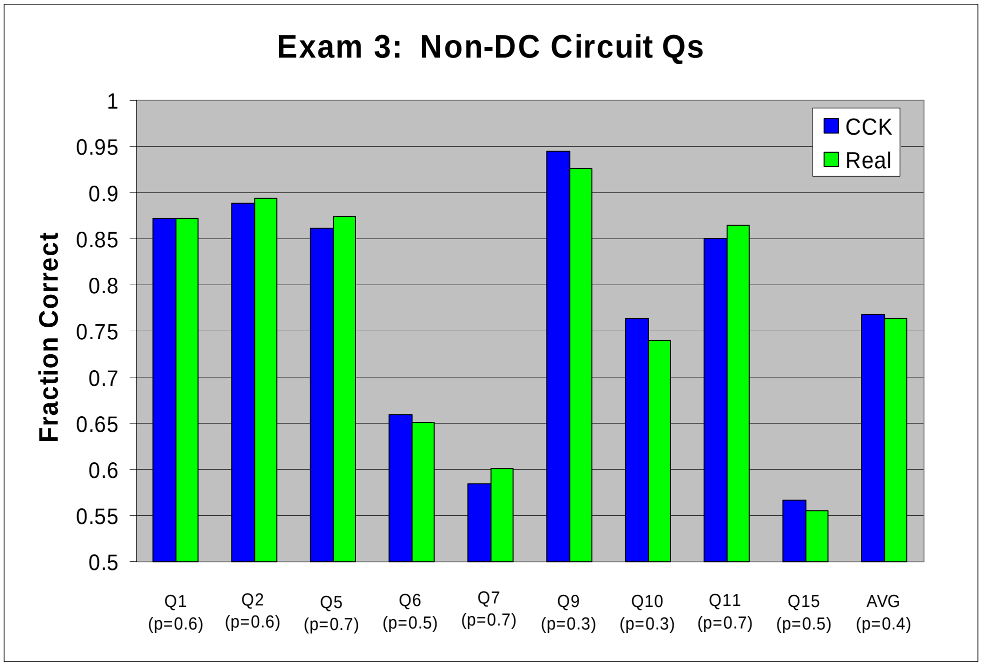

Figure 2 - Fraction correct of nine questions on exam not relating to DC circuits. No question yields a statistically significant difference. All p-values were found using the Fischer Test.

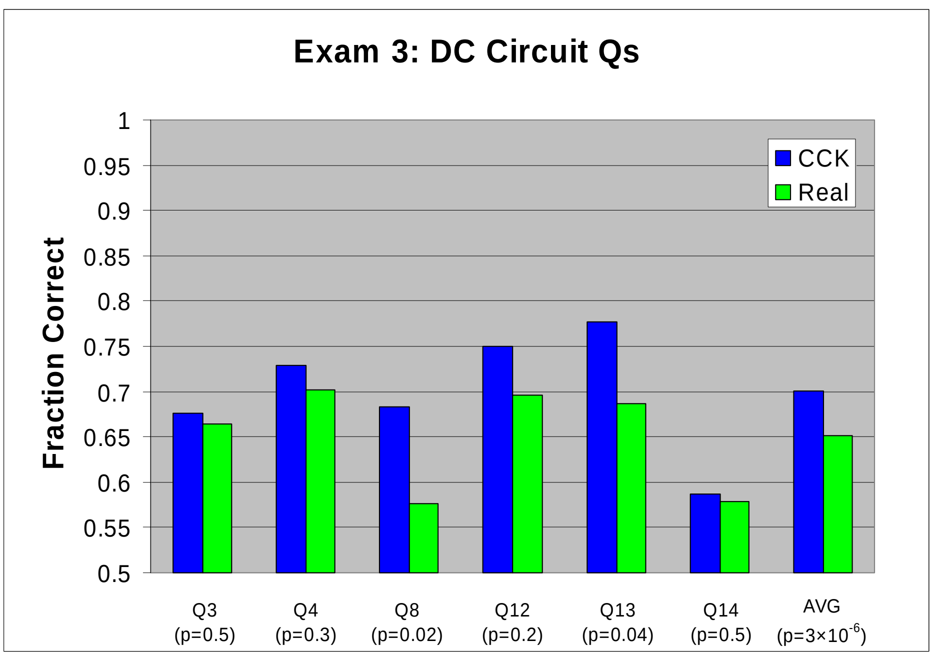

Figure 3 – Fraction correct of six questions on exam relating to DC circuits. Questions 8, 13, and the average of all six questions are statistically different. All p-values were found using the Fischer Test.

Analysis

Special attention was paid to verify that the experimental and control groups were performing the same on questions relating to DC circuits prior to this experiment and questions on other topics as well. Since DC circuits is not a stand-alone topic and incorporates ideas from current flow, voltage, resistance, batteries, and conductors, a difference in performance among the two groups on one of these topics may account for the differences on DC circuit questions in the end.

From the six questions on the BEMA exam, we can see no significant difference between the two groups prior to instruction. Both groups received the same instruction in the course until the first DC circuits tutorial, so it is safe to assume that both groups had the same conceptual understanding of DC circuits upon beginning the first circuits tutorial. In addition, both groups performed the same on the 9 non-DC circuit multiple choice questions on the exam mentioned earlier. It seems that this is sufficient evidence that both groups have an equivalent understanding of DC circuits prior to this experiment.

The other 6 questions on the exam relating to DC circuits show a statistically significant difference, where the CCK students outperform the students who used real equipment. Specifically, the CCK group outperformed the control group on questions 8 and 13 (see Appendix A). Both of these questions were not predicted to discriminate between the two groups, since neither question could be answered by utilizing an explicit model of current flow that CCK offers. Question 8 asks to predict the equivalent resistance of a circuit, and question 13 asks about the differences between measuring voltage and current in a circuit.

Why would students who used CCK do well on questions like this? One possible explanation is that the representation of the problem favored CCK students. Both of these problems represent a circuit in schematic form, which is often how circuits look when they are built using CCK. Students who used real equipment built circuits that were often messy and lacked the esthetics of straight lines and right angles that CCK circuits have. It could be that CCK students are more prepared to deal with problems that explicitly show a schematic.

On a similar note, question 12 was added to the exam in the hopes that it would discriminate between the two groups (see Appendix A). The question appears to favor the students using real equipment, since it asks them to match a circuit drawn as if it were a real circuit with its corresponding schematic. However, both groups perform similarly (p=0.2). It is not known why the students using real equipment did not outperform the CCK students, but a possible explanation is that this was not an explicit goal of the tutorial.

As noted earlier, some of the students were "playing" with the computer simulation prior to and after the tutorial. Some researchers have acknowledged the benefits of playing around, but like any educational tool, its benefits depend on its use.[15,16] Although how beneficial this playing was to conceptual understanding was not explicitly studied, it appears that it had no adverse affects on these students.

Much has been said on what the CCK students have gained, but nothing has been discussed of what these students "lost." At this point, no data has indicated that CCK students are at a disadvantage when using a computer simulation as opposed to real equipment. Again, the focus of this study was the conceptual understanding of DC circuits, and students' level of understanding was measured by their responses to multiple choice questions. It is possible that different forms of questions, such as open-ended questions that require a written explanation, may yield contradictory results. The simulations could possibly impede students from building working circuits from a schematic and testing that circuit. These aspects have not been tested in this type of environment, but a similar study shows that the students who used CCK performed better than students using a real lab on written explanations and building circuits.[10]

Conclusion

To summarize the results presented thus far, students who completed two circuits tutorials using a computer simulation in lieu of real laboratory equipment performed better at answering multiple choice questions on an exam than similar students who used only real laboratory equipment.

In addition to the study by Finkelstein, *et al.*, CCK has been shown to be successful at assisting conceptual development of DC circuits in two different classroom environments. The Finkelstein, *et al.* study used CCK in conjunction with an inquiry-based laboratory, whereas this study used CCK with "Tutorials in Introductory Physics." This by no means paints the entire picture of using computer simulations in lieu of real equipment. One simulation used in one environment is not sufficient to encapsulate the advantages and disadvantages of this tool.

Other data exist for this study that have yet to be analyzed. A brief attitude survey about tutorials was given to the students, and this may help quantify their view towards using simulations in lieu of real laboratory equipment. Written explanations to questions on an exam about circuits could help determine how the two groups verbalize their answers to circuit questions.

It is likely that computer simulations are context dependent, as most educational tools are. For now, the best we can do is to test these simulations in a number of different environments and study what students gain and do not gain by using them. Research in students passively observing computer simulations (i.e., students do not interact with the simulation) is another field that needs to be explored. In a separate, yet related experiment, Kathy Perkins is studying the effects of students seeing computer simulations in lecture in lieu of real lecture demonstrations.

The criticism against computers goes something along the lines of: “Why should we replace real lab equipment, which sometimes cost a few dollars, with a $2000 laptop and simulation?” The economic feasibility of this new educational tool is something to consider, but it should not hinder us from abandoning the idea all together. As computers become a more integral part of society, such alternatives to real equipment may become more practical.

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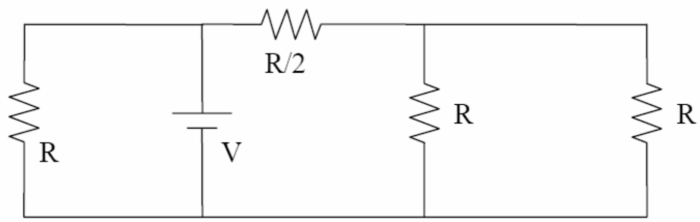
Appendix A

8. What is the total resistance seen by the battery in the following circuit? Notice that three of the 4 resistors are identical, all with resistance R, and the fourth resistor has resistance R/2. (Another way to ask the question is: The current through the battery can be written as $I = \frac{V}{R_{tot}}$. What is R_{tot}?)

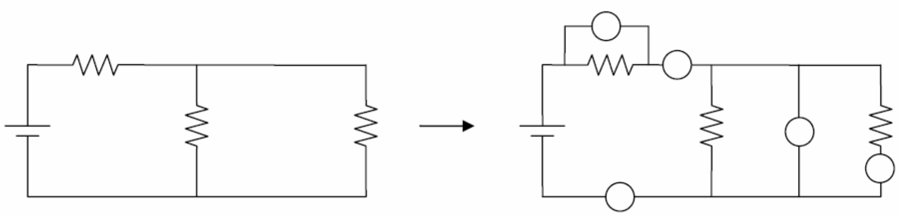


(A) R (B) 2R (C) 3.5R (D) R/2 (E) None of these

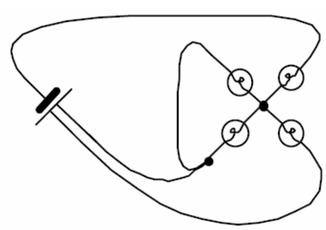
0001-9

13. An electrician wishes to measure the currents and voltages in a circuit by placing voltmeters or ammeters in various locations in the circuit. She places an ammeter or a voltmeter in each of the 5 locations shown. In order not to alter the currents and voltages that she wishes to measure, she should use...

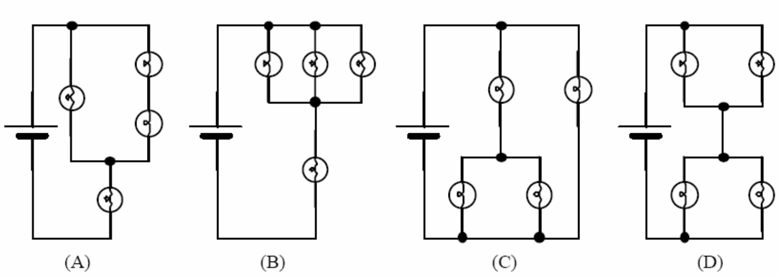
(A) exactly 1 voltmeter and 4 ammeters.
(B) exactly 2 voltmeters and 3 ammeters.
(C) exactly 3 voltmeters and 2 ammeters.
(D) exactly 4 voltmeters and 1 ammeter.
(E) either a voltmeter or an ammeter in any of the 5 positions. It doesn't matter which instrument she places where; the currents and voltages in the circuit will not be affected.



12. To the right is a circuit diagram drawn in an unusual way.



Pick the standard circuit diagram below that represents this same circuit.



None of these diagrams represents the circuit above.

(E)

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