# Can Computer Simulations Replace Real Equipment in Undergraduate Laboratories?

N. D. Finkelstein, K. K. Perkins, W. Adams, P. Kohl, and N. Podolefsky

*Department of Physics*
*University of Colorado, Boulder*

**Abstract.** This paper examines the effects of substituting computer simulations in place of real laboratory equipment in the second semester of a large-scale introductory physics course. The direct current (DC) circuit laboratory was modified to compare the effects of using computer simulations with the effects of using real light bulbs, meters and wires. Three groups of students, those who used real equipment, those who used computer simulations, and those who had no lab experience, were compared in terms of their mastery of physics concepts and skills with real equipment. Students who used the simulated equipment outperformed their counterparts both on conceptual survey of the domain and in the coordinated tasks of assembling a real circuit and describing how it worked.

## INTRODUCTION

Since the introduction of the microcomputer several decades ago, researchers and educators have developed, explored, and studied mechanisms for employing computers in the classroom. Over this time, computers have made their way into nearly every element of university courses in physics. Microcomputers have been used to augment large-scale lectures,[1] to promote individual student development[2] and seemingly everything in between.[3] One of the most common applications of computers has been to supplement recitations or laboratories in large-scale introductory physics courses.[3,34,5] These applications have included using computers to facilitate data acquisition, to provide real-time data display, to analyze these data, and to simulate complex phenomena. Such efforts have been shown to be as or more effective than their non-computer based counterparts, be they traditional or reformed, PER-based activities.

While computers have been used to supplement labs, we examine the effectiveness of completely replacing traditional equipment with computer-based simulations. Given the constraints (and large expense) of traditional labs, we explore whether it is possible to achieve the conceptual learning gains and mastery of mechanical skills with real equipment by working with computer simulations.

The following study took place in a traditional large-scale introductory algebra-based physics course at a large research university. The course was the second in a sequence of two, covering electricity, magnetism, optics and modern physics. Students, typically in their 2$^{nd}$ or 3$^{rd}$ year of study, received 5 credit hours for participating in three lectures and one integrated two hour laboratory / recitation section per week. Weekly homework assignments were the traditional end-of-chapter style questions, offered and graded by a computer system (CAPA).[6] Two instructors and 7 TAs were assigned to the 363 students enrolled in this course that met for 15 weeks.

The laboratories where this study occurred were offered every other week, alternating with the recitation sections. Six laboratory sessions were offered over the course of the term. The laboratories themselves had recently been revised by the lead author in order to emphasize an inquiry-based approach. The labs emphasized discovery rather than verification[7] and included some elements of "Scientific Community Labs".[8] This study occurred in the second laboratory of the course: DC-circuits. Students engaged in a series of exercises including: examining resistors in series and parallel, building a simple circuit and then predicting, observing and reconciling its behavior as various elements (resistors or light bulbs) were added or rearranged, and finally developing methods to measure resistance in multiple ways in these circuits. The goals of the lab were for students to develop an understanding of simple circuits (the concepts of voltage, current, and series, parallel and equivalent resistance), to develop the skills associated with connecting light bulbs, resistors and wires in various combinations, and to collect data and make arguments about these circuits' behaviors. Each lab began with students turning in pre-lab work and asking TAs questions about the material.

Some of the students in this study worked with a computer simulation in lieu of real equipment. The simulation, the Circuit Construction Kit (CCK), is part of the Physics Education Technology (PhET) project at the University of Colorado. The PhET project has developed approximately 35 research-based simulations which are available online.[9] These simulations are highly interactive, engaging, and open learning environments with animated visual feedback to the user. They emphasize students constructing conceptual models through a physically accurate, highly visual, dynamic representation of the physics. The PhET simulations are research-based, tested both in interviews of students and in-class use, and go through several design cycles. More on the PhET project and the research methods used to develop the simulations is available in ref 9. The Circuit Construction Kit includes an open workspace where students can place resistors, light bulbs, wires and batteries. Each element has operating parameters (resistance, voltage, etc.) that may be varied by the user and measured by a simulated voltmeter and ammeter. The underlying algorithm uses Kirchoff's laws to calculate current and voltage. Moving electrons are explicitly shown to represent current flow (and conservation). A screen shot appears in Figure 1.

**FIGURE 1.** PhET simulation: Circuit Construction Kit.

## STUDY DESIGN

Each of the fifteen sections of the algebra-based introductory physics course conducted the DC-Circuits lab. The sections were split into experimental conditions: CCK, (4 sections; N= 99 students) which conducted the laboratory with the simulations, and traditional conditions, TRAD, (6 sections; N = 132 students) which conducted the laboratory with real equipment. (The remaining 5 sections participated in the labs in slightly varied conditions, but are not included in this study for the sake of brevity.)

Each student was assigned a pre-lab activity, which varied by section (CCK or TRAD). Three of the four questions on the pre-lab were identical; the fourth question, which asked students to make a light bulb light with battery and a single wire, varied. The traditional group was asked to draw a circuit that would light the bulb; the CCK students were asked to build the circuit using the simulation and submit the results. All students turned in their assignments at the beginning of their lab section.

The DC-Circuits lab was matched for the two groups. The written introduction to the equipment was the same for both groups, each receiving instructions on reading resistors etc. However, additional instructions on operating the simulation were provided to the CCK group. The actual laboratory activities (challenges and wording) were the same except the traditional groups were instructed to manipulate real equipment, the CCK groups to manipulate simulated equipment. Students worked in groups of two to four.

The last 30 minutes of each laboratory section was set aside for students to engage in a challenge worksheet consisting of three questions. The main challenge for *all* students was to build a circuit (shown in Figure 1) using *real* equipment, and describe what happens and why when the circuit was broken where the switch is shown. Notably the CCK group had no formal exposure to this equipment before this challenge. As an added control, this same challenge sheet was given to students (N=107) in the calculus based introductory sequence (electricity and magnetism), during 4 of the recitation sections. The calculus based course has a detached laboratory course which students generally had not yet taken; however, these students had spent three lecture periods (including a demonstration of this very circuit), and a homework set covering DC-circuits before attempting the challenge worksheet.

## DATA

The following data were collected and analyzed during the course of this study:

- Pre-lab worksheets (for each student)
- Observational notes of the sessions (both by TAs and by researchers in this study)
- Timing data. How long it took students to build the assigned circuit as a group and to complete the challenge sheet at the end of the lab individually

- Lab challenge write-ups (written up and turned in by each student)
- Three questions on DC-circuits on the final exam issued 12 weeks later.

Here, we report only on the timing, the performance on the challenge worksheets, and the performance on the final exam questions.

## Circuit challenge:

During the laboratories, all students completed a challenge worksheet where they were asked in their groups to build the circuit shown in Figure 1, show the TA, and then break the circuit at the point designated by the switch. Students answered the following question: "In 50 words or more, describe what happens and why the bulbs change brightness as they do. You may use words and formulas..." and turned in their answers individually. Meanwhile TAs were given observation sheets that included a section asking them to report on how long it took students to complete the circuit challenge, "For each group in your section (i.e. groups 1-10 or so), please note roughly how long it took them to complete the circuit challenge." The same challenge and observations sheets were provided to students and TAs for the calculus based introductory physics course.

*Timing:*

The timing data -- how long it took groups of students to build the circuit, break the circuit and write-up the challenge -- are plotted in Figure 2. The averages for the experimental condition (CCK), the group using traditional equipment (Trad), and calculus-based course sections with no lab (No Lab) are plotted.

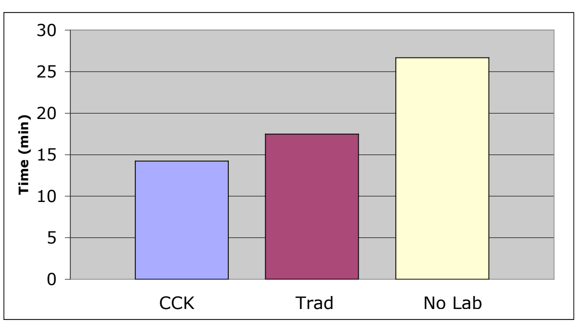


**FIGURE 2.** Time for students to build a circuit with real equipment and write about it. Mean times for all groups plotted. Student times for individual groups varied ±7 minutes for most all (90% or more) of the groups.

*Evaluation of write-ups:*

Each circuit challenge write-up was evaluated by the authors as to overall correctness on a scale from 0 to 3.[10] 0 represented no demonstrated knowledge of the domain, while 3 represented correct and complete reasoning. The fraction of students scoring 0, 1, 2,and 3 are reported in Figure 3 for each of three groups, the experimental group (CCK), the traditional group (Trad) and the calculus-based group (No Lab).

The average score for the experimental group (CCK) is 1.86 and the real-equipment group (Trad) is 1.64 – a statistically significant shift ($p<0.03$). The calculus-based no-lab group averaged 1.91 (significantly different than the traditional group on a two tailed z-test, $p< 0.02$).

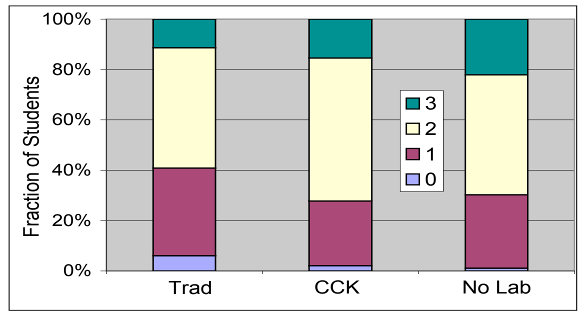


**FIGURE 3.** Performance on write-up of circuit challenge (0- no demonstrated knowledge to 3 – correct / complete)

## Final Exam:

Referring to a schematic drawing of a series and parallel circuit, like the one shown in Figure 1 (but in schematic form and with a closed switch), students were asked to: (q1) rank the currents through each of the bulbs, (q2) rank the voltage drops across the bulbs in the same circuit, and (q3) predict whether the current through the first bulb increased, decreased or remained the same when the switch was opened.[11] Figure 4 plots student performance for the experimental (CCK) group and the traditional (TRAD) group for each of these three questions (q1, q2, q3), and their performance on the remaining 26 questions

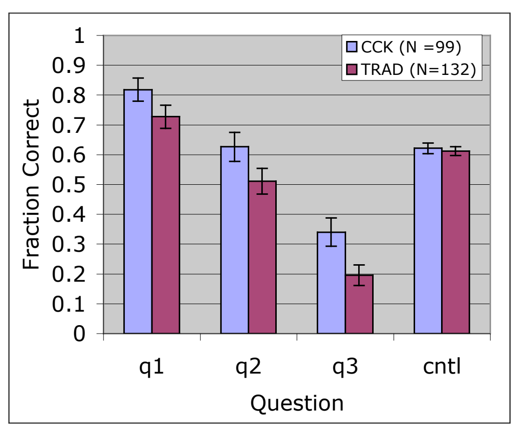


**FIGURE 4.** Student achievement on three conceptual circuits questions on final exam (q1-q3) and the remaining 26 questions on final (cntl).

on the final (labeled "cntl"), which covered other material in the course. The mean for all three questions is 0.593 ($\sigma$=.27) for CCK and is 0.476 ($\sigma$=.27) for TRAD groups; $p<0.001$. Notably, these results occur roughly more than two months after the lab was conducted, on the final (after many other forms of exposure to the same material – lectures, homework, exams, and studying).

## DISCUSSION

While only three forms of data are presented here, the other data in this study (observations of the laboratories, pre-lab work, and detailed analysis of the challenges) appear to corroborate these findings. In short, we might answer the question posed in the title in the affirmative—in the right conditions, simulations can be substituted effectively for real laboratory equipment.

In this particular case, we might make the stronger claim: it is preferable for students to work with simulations over real light bulbs and resistors. We are not claiming that all circuits labs ought be replaced, but rather the conventional wisdom that students learn more and need the hands on experience is not borne out by measures of mastery of the content, nor their ability to construct circuits.[12] In a hands-on, inquiry based lab, students using the simulations learned more content than did students using real equipment.

No less significant is student facility at actually constructing physical circuits. The data suggest that students working with simulations are indeed no slower at constructing and writing about circuits. In addition to more correctly and thoroughly writing about the circuits, the students take less time on average than their counterparts at building and describing these circuits.

Others have suggested a list of important characteristics of computer-based activities and simulations – from actively engaging the students to providing tools to reduce unnecessary drudgery.[5,13] To this list we add two more items which might begin to explain our findings. Computers can:

- make visible the models that are useful for forming concepts, and
- constrain the students in productive ways.

The first point is demonstrated by the CCK simulation where making the current flow (moving electrons) visible to the students emphasizes that current is conserved. As to the second point, we note that students' "messing about" can be productive in the simulation where explorations lead to investigation of circuit properties. (Notably, students' investigations are constrained to the concepts at-hand.) With the real equipment "messing about" can be unproductive (intellectually) and students end up building wire-bracelets. As Otero finds, students use computer simulations productively to produce conceptual models that are then effectively applied to physical (dare we suggest "real world') applications.[14]

We do not suggest that simulations necessarily promote conceptual learning and facility with equipment, but rather they are useful tools for a variety of contexts which can promote student learning. Redish asks "Is the computer appropriate for teaching physics?"[15] – we suspect its time may have arrived. "To simulate or not to simulate?" asks Steinberg. We answer yes… providing simulations are applied in the appropriate contexts.


## ACKNOWLEDGEMENTS

This work was conducted with the support of the NSF, the Kavli Foundation, and the University of Colorado. The authors are grateful to Carl Wieman, the PhET team (particularly Sam Reid, author of CCK, and Ron LeMaster, lead software architect for the project) and members of the newly formed Physics Education Research Group at Colorado (PER@C).


## REFERENCES


[1] D.R. Sokoloff and R.K. Thornton, Phys.Tch,**35**,340 (1997).
[2] R.N. Steinberg, G.E. Oberem and L.C. McDermott, *AJP*. **64** (11) 1370 (1996).
[3] A useful starting point to find references: Z. Zacharia and O.R. Anderson, AJP 71(6), 618, 2003.
[4] P. Laws, *Physics Today*, Vol. 44, No. 12, December 1991 D. Sokoloff and R. Thornton, AJP **58**, 858 (1990)
[5] E. F. Redish, J. M. Saul, and R. N. Steinberg, AJP. **65** (1997) 45-54.
[6] http://www.lon-capa.org/
[7] E. Lewis Multi-Initiative Dissemination Project http://www.cchem.berkeley.edu/midp/
[8] R. Lippmann, Dissertation. University of Maryland 2003. http://www.physics.umd.edu/rgroups/ripe/perg/dissertations
[9] C. Wieman, Physics Education Technology Project, http://www.colorado.edu/physics/phet
[10] Five graders each evaluated these responses, grading at least one section of each type (CCK and TRAD).
[11] These questions follow from those in the ECCE (Thornton& Sokoloff) and are part of Workshop Physics: http://physics.dickinson.edu/~wp_web/wp_homepage.html
[12] We suspect there are some benefits to using real equipment, but that we did not measure them here.
[13] R.N. Steinberg, Am. J. Phys. **68**, S37-S41 (2000)
[14] V. Otero, (in press). *Proceedings of the International School of Physics "Enrico Fermi",* edited by M. Vicentini and E.F. Redish (IOS Press, Amsterdam), July, 2003,
[15] E.F. Redish, *Computers in Physics* **7** (December 1993)