Step-Based Tutoring Software for Complex Procedures in Circuit Analysis

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***Abstract*— (Innovative Practice, Work in Progress.) Step-based tutoring systems, in which each step of a student's work is accepted by a computer using special interfaces and provided immediate feedback, are known to be more effective in promoting learning than traditional and more common answer-based tutoring systems, in which only the final (usually numerical) answer is evaluated. Prior work showed that this approach can be highly effective in the domain of linear circuit analysis in teaching topics involving relatively simple solution procedures. Here, we demonstrate a novel application of this approach to more cognitively complex, multi-step procedures used to analyze linear circuits using the superposition and source transformation methods. Both methods require that students interactively edit a circuit diagram repeatedly, interspersed with the writing of relevant equations. Scores on post-tests and student opinions are compared using a blind classroom-based experiment where students are randomly assigned to use either the new system or a commercially published answer-based tutoring system on these topics. Post-test scores are not statistically significantly different but students prefer the step-based system by a margin of 84 to 11% for superposition and 68 to 23% for source transformations.**

Keywords*— linear circuit analysis; computer-aided instruction; step-based tutoring; learning by example

I. Introduction

Prior studies have shown that step-based tutoring systems can provide superior learning gains relative to more common and traditional computer-based instruction using an answer-based approach [1]. The step-based approach however requires that feedback and hints be provided in response to each step of a student's work, necessitating specialized interfaces that can accept those steps in a variety of forms. Prior applications of this method have focused mainly on entering numerical or multiple-choice answers, identifying elements in series or parallel by marking them, and sometimes on sets of equations or sketches of waveforms or Bode plots [2-8]. More complex forms of circuit analysis, involving repeated modifications of the circuit diagram itself, have yet to be addressed using step-based systems. Such analyses are more cognitively complex and demanding due to their multi-step nature and the need in some cases to visualize in advance how a given transformation of a circuit will enable further analysis. Other computer-based systems developed to date to support linear circuit analysis instruction have not supported such complex analyses [9-26].

Complex problem solving procedures include superposition analysis of linear circuits, where all but one independent source are "turned off" at each stage to determine the voltages and currents due to each such source acting independently [27]. These "partial" quantities are then summed in the last step to find the desired voltages and currents (denoted "sought quantities"). "Transformations" of the sought voltages and currents into the opposite type of unknown, using Ohm's law or similar relationships, are often required in this process to enable complete simplification of the circuit to the elementary single node-pair or single-loop forms. Another complex type of analysis involves source transformations, where a voltage source in series with an impedance is converted to an equivalent consisting of a current source in parallel with the same impedance, or vice versa, in order to permit more complete simplification of a circuit problem to facilitate its analysis [27]. Both procedures involve an intricate interwoven sequence of circuit modifications and equation writing.

The goal of this study is to determine if a workable system can be devised that guides and enables students to carry out these complex types of analyses with suitable feedback at each step, while using automatic problem generation to provide an unlimited supply of problems and isomorphic examples at multiple levels of difficulty. Further we wish to compare the ability of students to solve relevant exam problems after using such a system or after using a traditional answer-based system, and compare student opinions of each system.

II. Step-Based Interfaces

Generation of random circuit topologies and element values for both examples and exercises followed our previously developed three-step algorithm [2, 3], modified to ensure that both superposition and source transformation problems could be simplified using those methods to single node-pair or single loop circuits amenable to current or voltage division (or similar) solution approaches. For both topics, problems were designed to have three progressive levels of difficulty to help build student confidence. Videos (housed on YouTube, ~10 min. each) were provided of the instructor working a typical

This work was supported by the National Science Foundation through the Transforming Undergraduate Education in Science, Technology, Engineering and Mathematics Program under Grant Nos. 1821628, 1044497, and 1323773.

problem at each level using the system to demonstrate both the operation of the interfaces and the methods and sequences needed to work the problems [28]. No introductory interactive tutorials were provided for either topic, so that students relied mainly on lectures and a textbook [27] to learn the methods. Examples presented a scrollable series of circuit diagrams with accompanying explanations (specific to the problem in question) of each step of the process.

For superposition, the required solution steps [27] are: 1) A problem (circuit diagram) with multiple independent sources is presented, showing one sought voltage or current to be calculated. 2) Optionally, students may enter the circuit editor in a pre-simplification mode to combine elements in series or parallel before "killing" sources. In pre-simplification mode, a sought current that prevents the combination of passive elements in parallel or a sought voltage that prevents the combination of passive elements in series can be converted to the opposite type of sought variable by defining a new sought variable of the appropriate type and then deleting the original one. Students are then prompted to write an Ohm's law type of equation (called an auxiliary equation) in the equation editor to express the deleted variable in terms of the new one before the old one is deleted. They may then continue simplifying as far as possible (perhaps performing additional sought variable transformations) and finally exit the editor. After each simplification or equation-writing step, they are given immediate feedback on the correctness of that step. Further, they are given instructions as to what to do next. Errors are counted, and making more than a certain number causes them to lose credit for that problem (though they can still finish it if they wish). There is no penalty for the loss of credit; they must simply complete a completely new problem of the same type without excessive errors. They can similarly give up at any time and view a complete solution of the problem they are attempting (similar to examples) without penalty.

3) Students must then re-enter the circuit editor in the "source killing" mode, where they need to de-activate all but one source by changing voltage sources to shorts or current sources to open circuits, respectively. Feedback is given and errors are counted. 4) They then exit the circuit editor and typically re-enter it in the pre-simplification mode used in step (2), where additional simplification is normally possible. 5) Once they reach a single node-pair or single loop circuit, they exit the editor and write an equation for the partial value of the sought quantity using the template-based system described elsewhere [3, 6]. (The rationale for using problems without dependent sources that can be reduced to single node-pair or single-loop form is that if a full nodal or mesh analysis is required for each independent source, the required work would be greater than doing such an analysis directly without using superposition.) Students have a limited number of attempts to write the correct equation and lose credit if they exceed that number. 6) After writing a correct equation, they evaluate it numerically and compute values of any deleted sought variable(s), using the auxiliary equations as needed. 7) They are then presented with the (possibly pre-simplified) circuit with all sources active, and are instructed to repeat steps (3)-(6) for each source. 8) Once they have analyzed each source, they must add the partial values and enter the total value of the sought quantity, which is again checked. A screen shot of one step is shown in Fig. 1. Both detailed written help and video help is available at every step to guide students.

For source transformation, students are shown a circuit with multiple independent sources that can be reduced to a single node-pair or single loop circuit. They immediately enter the circuit editor in the pre-simplification mode (but are not allowed to do sought variable transformations in this case, as

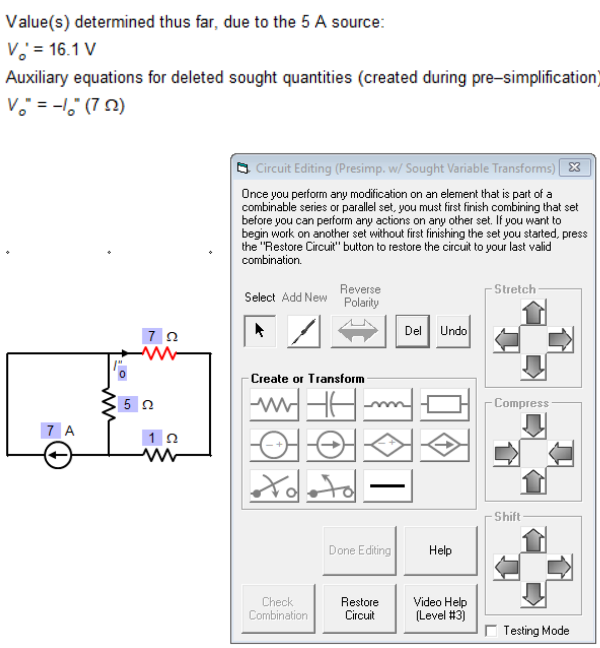

Fig. 1. Superposition example. User has already killed two of the three sources and has just converted a sought voltage that prevented series combination of resistors to a sought current that permits same by writing an auxiliary equation for the former in the equation entry system (shown at top). They are preparing to combine resistors in series in the circuit editor to achieve a single node-pair circuit. The sought variable was automatically double primed to denote that it is a partial value due to one source.

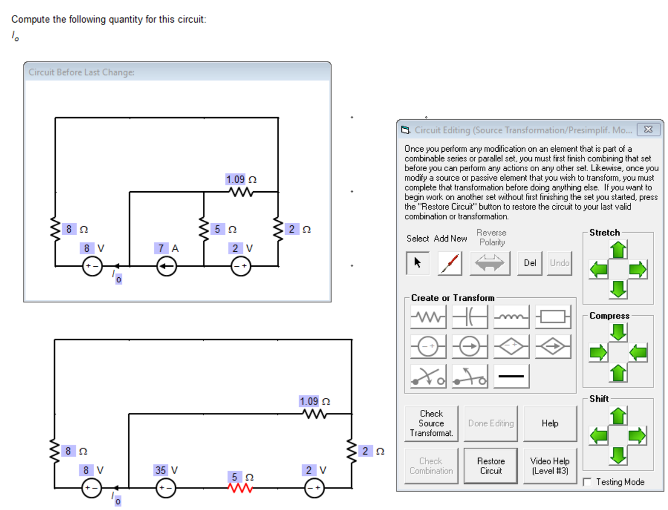

Fig. 2. Source transformation example. User has just transformed a 7 A source in parallel with an 8 Ω resistor into a 35 V source in series with the same resistor (having "stretched the circuit horizontally to make room on the grid), and is about to check that action in the circuit editor. The last valid circuit is always shown in the window above for easy reference.

they should not be needed). They are required to simplify all passive elements and sources that can be combined in series or parallel (as that should always be done prior to source transformations), and are clearly notified of that requirement if they try to transform sources prematurely. They are then allowed to transform sources by changing the voltage source to a current source (or vice versa) and dragging the new source and/or passive element to change them from being in series to being in parallel (or vice versa), as appropriate. As in the superposition case, detailed written help and video help is available at every step.

In many cases there is not room on the grid used in the circuit editor to complete a transformation. Therefore students are allowed to shift the entire circuit in any direction or automatically "split" it along a specified line to make room to do the transformation. A new value must be entered for the transformed source using the relation $V = I R$, where V and I are the values of the voltage and current source, respectively, and R is the resistance being transformed. (AC circuits are supported for all analysis techniques. In this study, however, only DC circuits were used). After each transformation, its validity is checked, detailed feedback is given on any errors, and errors are counted.

Some transformations are "legal" but do not lead to further possibilities of simplification. In this case, students are warned that they will either need to complete another transformation that will then allow simplification, or they must reverse the step they just completed. They are then allowed and required to combine any elements that are newly in series or parallel, and then repeat the transformation process as needed until they arrive at a single node-pair or single loop form. Once they reach that goal, they exit the circuit editor and write an equation for the sought quantity and enter its numerical value as described earlier. Giving up without penalty is again possible at any stage. Fig. 2 shows a sample screen shot (note the help and video help buttons on the interface).

III. Comparison to answer-based system

A. Experimental Design

To evaluate these new modules (DC Superposition and DC Source Transformations), a blind randomized experiment was carried out at Arizona State University in Spring 2019 in a class of ~64 students taught by the first author. Students were randomly assigned to two groups, denoted A and B. Group A was assigned to complete the DC Superposition tutorial in the step-based Circuit Tutor under study as part of one homework assignment, and three problems in a commercial, answer-based tutoring system (WileyPLUS, [29], for the book by Irwin & Nelms [27]) on DC source transformations. Group B was assigned to complete the DC Source Transformations tutorial in Circuit Tutor and three problems in WileyPLUS on DC superposition (Circuit Tutor requires three or potentially more problems, depending on the number of mistakes made). Thus, both groups did a roughly equivalent amount of work in both systems on these two topics.

The WileyPLUS problems were selected to correspond as closely as possible to the levels of difficulty in Circuit Tutor, and WileyPLUS was configured to allow an unlimited number of attempts at the correct numerical answer. Some element values were randomized in WileyPLUS for each student, but they were not changed between successive attempts. In both systems students were encouraged (but not required) to look at examples before working problems, either in the textbook (for WileyPLUS) or in Circuit Tutor for the students using that system on a given topic. They were also encouraged but not required to view videos of problems being worked either within WileyPLUS or within Circuit Tutor. Both groups had been assigned to read the textbook discussion and to attend lectures on both topics prior to undertaking the homework. The tutorial assignment constituted all of the homework on these topics. Students did not have access to the system they were not assigned to use on a given topic, though two students who had worked ahead or done beta testing on a system they were not assigned to use were excluded from the study.

No pre-test was used, and the blindly graded post-test consisted of one 12-point problem on each topic as part of a midterm exam worth 100 pts. total given the day after the homework due date. The relevant exam problems were taken from a different textbook to avoid any bias in favor of either system. Scores on the exam problem on each topic were evaluated separately, so that two separate experiments were conducted. The comparison group for one topic was the treatment group for the other, but as the two topics involve different circuit analysis principles, we believe the two experiments to have been essentially independent of each other. A survey of student opinions on the two homework systems (for these two topics) was designed by the evaluation team and assigned for 10 pts. of extra credit on the 100 pt. homework assignment. It was due three days after the homework due date (to avoid interfering with the exam). The response rate was 67%.

B. Satisfaction and Utility of System

When asked what system students preferred working within, the majority listed Circuit Tutor when compared to WileyPLUS for both source transformations (68% compared to 23%) and for superposition (84% compared to 11%). There were 33 students (out of the 42 who responded with a preference) that preferred Circuit Tutor. Using open-coding to analyze the qualitative data, 39% reported that Circuit Tutor walked them through the problems and allowed them to follow along, 23% liked the examples given, 21% liked that the system was interactive, 10% liked the immediate feedback, and 6% liked how they solved the problems. Some illustrative examples of why students preferred Circuit Tutor were:

- *Because the questions are broken down into several steps, I find Circuit Tutor to be more helpful for developing a systematic approach for problem solving.*
- *If I could not figure out a Circuit Tutor problem, the walk through at the end would usually clear things up. WileyPLUS had none of that, so I felt like I was on my own.*
- *Circuit Tutor allows for a more rapid feedback to where the mistakes you have made and how to learn from them. Wiley is much less kind with its feedback and precision that is needed for the answer is less than ideal.*

- *Circuit Tutor gives me better results in terms of information retention due to its educational game-like format.*
- *I enjoyed Circuit Tutor because it is interactive and forces you to visualize the concepts as you modify the circuit and solve the problem, which aides [sic] in overall comprehension and understanding.*

For those who preferred WileyPLUS (*N*=9), open-coding the qualitative responses revealed that 67% said it was because they could make more mistakes, 22% said that they liked working the problems by hand, and one person (11%) said that it was easier to navigate. Some illustrative examples include:

- *I preferred WileyPLUS because I prefer to work out the circuit by hand. I find myself making mistakes on paper that I can easily erase and correct, but when I make them on Circuit Tutor I have to start a new problem when this happens. Writing things down also helps me remember how to do things better in the future, and when I do them on Circuit Tutor I have difficulty remembering what I did when I advance to a new problem.*
- *I preferred WileyPLUS because I was allowed to make mistakes without being penalized and having to start over.*

C. Impact of the System on Student Learning

Sixty-two students were randomly assigned to one of two treatment groups (see Table I below). The results indicate that there were some statistically significant differences in the superposition homework completion rates [$t(62)=2.10$, $p=0.04$] such that there were higher mean completion rates in Group A students using Circuit Tutor ($M=0.94$) compared to Group B students using WileyPLUS ($M=0.75$). There were marginally significant differences in the source transformation homework completion rates [$t(62)=1.83$, $p=0.07$] such that there were higher mean completion rates in Group A students using WileyPLUS ($M=0.88$) compared to Group B students using Circuit Tutor ($M=0.69$).

Furthermore, findings indicate that there were no significant differences in the superposition homework scores regardless of the platform. There were, however, differences in source transformation homework scores [$t(54)=2.65$, $p=.01$] such that there were higher scores in Group A students using WileyPLUS ($M=31.43$) compared to Group B students using Circuit Tutor ($M=23.96$). Lastly, there were no significant differences on the post-test exam item scores between groups.

IV. Conclusions

We have extended a step-based tutoring system to cover topics that involve an intricate sequence of steps including multiple edits to a circuit diagram and ultimately writing equations for it. Detailed feedback is provided to students at each step so that they do not waste time continuing to analyze a circuit after making a fatal error in prior stages. Automated problem and solution generation is employed to provide each student with an unlimited supply of both problems and fully worked and explained examples. The system provides that no two students get the same problems, to discourage copying or cheating. The step-based approach also ensures that students actually use the specified problem-solving approach, which is often not guaranteed in answer-based systems.

The new system is at least as effective as a mature commercial system in terms of post-test scores (based on the limited evaluation used here), and is strongly preferred over the commercial system by students for both of the new tutorials. A more comprehensive post-test might provide a better evaluation, and the system can very likely be improved in future work. The source transformations tutorial, in particular, was completed only on the day it was assigned, so is far from fully developed or mature.

Some possible improvements would be as follows, at least some of which are planned to be implemented or tested: 1) Give more detailed explanations of why the system chooses the steps it does when doing examples, especially in source transformations (students have requested this); 2) provide introductory, interactive tutorials on both topics including multiple choice questions; 3) incorporate qualitative questions and/or requests for students to summarize the procedures they are learning during the tutorials; 4) provide a "transcript" of student work during the tutorial showing their correct and incorrect responses, for use in studying (and possibly for educational research); 5) illustrate practical applications of the material being studied to improve motivation; 6) incorporate some of the "desirable learning difficulties" discussed, e.g., by R. Bjork and co-workers [30-32], such as spacing (requiring different levels of a tutorial to be completed days apart, not all together), interleaving (mixing content on two different analysis techniques rather than presenting them in sequence), and pre-testing; 7) adaptively adjust the number and/or types of required problems based on evaluation of student performance; and 8) provide an instructor dashboard showing student performance and typical errors so in-class instruction can be adjusted. For source transformations, we might also develop an exercise in which students only identify possible and/or useful transformations without actually carrying them out.

Similar modules to derive Thévenin and Norton equivalent circuits and to solve transient problems are in development.

TABLE I. Summary of Randomized, Blind Experiment Comparing the Two Tutorial Systems.

	Superposition		**Source Transformation**	
	Circuit Tutor	WileyPLUS	Circuit Tutor	WileyPLUS
Group	A (*N*=32)	B (*N*=32)	B (*N*=32)	A (*N*=32)
HW Completion Rates	94%*	75%	69%	88%†
HW Score (0 to 33)	29.22 (9.52)	30.86 (5.32)	23.96 (14.06)	31.43 (4.93)*
Midterm Exam Item Score (0 to 12)	6.59 (4.49)	6.29 (2.80)	6.71 (4.58)	5.91 (2.41)

Note: † $p < 0.10$; * $p < 0.05$. Values in parentheses are standard deviations.

ACKNOWLEDGMENTS

We thank J. Aberle, G. Abousleman, M. Ardakani, J. Blain Christen, S. Chickamenahalli, S. Dahal, A. Ewaisha, R. Ferzli, G. Formicone, S. Goodnick, R. Gorur, O. Hartin, S. Jayasuriya, G. Karady, R. Kiehl, H. Mao, B. Matar, A. Maurer, D. Meldrum, B. Moraffah, C.-Z. Ning, S. Ozev, L. Sankar, A. Shafique, W. Shi, D. Shin, M. Tao, C. Tepedelenlioglu, T. Thornton, G. Trichopoulos, D. Vasileska, C. Wang, Y. Weng, M. Wong, Yu Yao, Hongbin Yu, and Hongyu Yu for using our software in their sections of EEE 202 at ASU. We thank W. Thompson II and Y. Astatke for using our software at Morgan State University, H. Erives-Contreras for using it at University of Texas at El Paso, P. Andrei for using it at Florida A & M University/Florida State University, H. Underwood, R. Fish, and D. Pratt for using it at Messiah College, J. D. Irwin for using it at Auburn University, J. Ross and H. Xu for using it at University of the Pacific, V. Gupta for using it at the University of Notre Dame, A. Holmes for using it at the University of Virginia, G. Gilmore for using it at North Carolina A&T State University, O. Nare for using it at Hampton University, and T. Frank and B. Matar for using it at Glendale, South Mountain, and Chandler-Gilbert Community Colleges. We thank Don Fowley of John Wiley & Sons, Inc. for supporting the project.

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