Impact of Step-Based Tutoring on Student Learning in Linear Circuit Courses

B. J. Skromme, V. Seetharam, X. Gao,
B. Korrapati, B. E. McNamara
School of Electrical, Computer, and Energy Engrg.
Arizona State University, Tempe, AZ 85287-5706, USA
skromme@asu.edu

Y.-F. Huang
Department of Electrical Engineering
University of Notre Dame
Notre Dame, IN 46556, USA

D. H. Robinson
School of Education
Colorado State University
Fort Collins, CO 80523, USA

Abstract— **A step-based tutoring system is being developed to improve student learning in elementary linear circuit analysis courses. The approach is based on the known importance of viewing worked examples or solutions in alternation with problem-solving exercises of the same type, to avoid excessive cognitive loads when learning a new skill. The system can generate an unlimited supply of circuit problems (with randomly varying topologies) similar to those in textbooks and corresponding fully explained solutions for both DC, AC, and transient analysis. Solution methods and topics include voltage and current division, node and mesh analysis, superposition, Thévenin and Norton equivalents, Bode plots, and Laplace analysis. Special pedagogical devices are used to reduce extraneous cognitive load when using the system, such as color-coding nodes and equation terms. Qualitative conceptual topics such as series and parallel connections are given special emphasis. The system has been used to date by over 2860 students in 71 class sections at 10 different colleges and universities of widely varying types, with generally very favorable student ratings. Evaluation has included a series of randomized, controlled trials in both laboratory and classroom settings to rigorously assess student learning gains as well as the impact of the materials on student motivation and preferences. Learning improvements of 0.72 std. deviations are found in comparison to a publisher-based homework system for node analysis, and 0.97 std. deviations for identification of elements in series and parallel compared to paper exercises.**

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

I. INTRODUCTION

Effective learning in large enrollment, fundamental and widely-taught courses such as linear circuit analysis is critical to improving overall retention and graduation rates in engineering programs. Our approach to help achieve this goal is to develop highly interactive, individualized computer-based instruction using the step-based tutoring approach as a substitute for traditional paper-based or publisher-based homework systems. Example-based learning is already known to be very important to developing systematic analysis skills, in combination with problem-solving [1-3]. We extend this traditional method in our system to use "*engaged examples*," where students have the option to view a complete, fully-worked and fully-explained solution to a problem at any time when they are unable to complete the problem on their own. At that point, students are highly invested in solving the specific problem in question (as opposed to traditional examples encountered *prior* to problem solving), and are therefore highly motivated to study the solution to find out where they went wrong or what they should have done next. A key feature is that students are never penalized for viewing these engaged examples, so that we can enhance their motivation and self-confidence. Students can "give up" and view such examples as many times as needed, from none at all to as many repetitions as they desire, due to our unique ability to generate an unlimited supply of new problems of the same type and difficulty, but completely different circuit layouts.

The *automated problem generation* approach (including automated generation of highly detailed solutions) is the key underlying technology that enables the system, in conjunction with specialized interfaces to easily accept many forms of analytical and graphical inputs for automated answer checking. Mastery learning of each topic is required, ensuring that students are well prepared for subsequent topics that depend on prior ones. The system adapts to the needs of each individual student by providing as many or as few exercises of each type as that particular student needs to attain mastery. Assessment of student learning and opinions has been carried out using a number of rigorous, randomized, controlled experiments in both laboratory and classroom-based settings, and has yielded substantial learning gains in comparison to both traditional paper-based and commercial publisher-based electronic homework systems.

II. BACKGROUND AND APPROACH

A variety of computer-based approaches has been utilized in prior work on instructional systems for linear circuit analysis [4-25]. Many of these have involved either a fixed set of pre-generated problems or have been algorithmic in nature, where one or a few element values are randomly varied in a given circuit problem and the computer assesses if the student has computed the correct answer for those specific values [5, 9, 11, 15-19, 21-25]. In particular, most commercial publisher-based systems are of this nature. Such "answer-based tutors" are known to be considerably less effective than the present step-

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based approach, where many different steps of the student's work are accepted and evaluated prior to the final answer [26]. Moreover, many of the prior studies did not include any evaluation of their effects on student learning, or did not include a measure of student ability in the experimental and control groups [5, 9, 11, 15-19, 21-25]. Some systems have also not been comprehensive and addressed only a narrow range of topics [15, 25]. Our goal (not yet fully attained) is to cover all of the topic areas in a traditional two-semester linear circuits course. Further, our system is designed to accept a wide range of input types, including graphical input of waveforms as a function of time, Bode plots, drawing or re-drawing of circuit diagrams (e.g., during simplification, source transformations, or superposition approaches), equations (using special template-based interfaces designed to provide scaffolding of the student work), simplified forms of equations, matrix equations, numerical answers, and multiple choice inputs. Nearly all prior systems have been limited to accept only numerical and multiple choice answers and equations in some cases [4, 5, 10-12, 15, 17, 18, 21-24, 27].

We feel that to maximize the effectiveness of any automated tutoring system, it is important to use design principles that build on existing knowledge about how students learn this type of subject. The principles of cognitive load theory suggest that an effective system should avoid overloading a student's working memory with too many items, so that appropriate complex schemas can be developed and stored in long-term memory to aid in future problem solving [2]. The used of worked examples helps to minimize this load, and thereby facilitates learning, as is well known [1-3]. Specifically, Anderson, Fincham, and Douglass posited that the learning of a new cognitive skill such as recognizing elements in series and parallel or solving circuit problems involves four overlapping stages [28]. In the first stage, students make analogies to solved examples to solve new problems. In the second stage, students develop abstract declarative rules to embody their knowledge, and in the third stage they create production rules to implement the declarative knowledge. In the fourth stage, they progress to recall specific examples from memory based on extensive prior experience, speeding up their performance. Learning from worked examples is highly important in the first two stages, but students must progress to active problem solving in the later stages [1]. Alternation between viewing of worked examples and working problems on their own is highly effective in the first two stages [1]. In our case, we extend these principles to use *engaged examples*, where students are shown fully explained solutions to the problems they are already trying to solve, in order to maximize their motivation and interest in the examples being shown. We also provide access to fully worked examples that are directly isomorphic to all assigned exercises.

Another goal of our system is to optimize long-term retention and the ability to flexibly transfer learned concepts and skills to new situations and problem types. To do so, we have begun to incorporate some of the "desirable difficulties" discussed by Bjork into the learning process [29]. For example, the use of frequent low-stakes testing, even prior to learning, is known to be highly effective in stimulating learning [30]. All of our modules will therefore incorporate both pre- and post-tests (though in some cases they are not yet implemented, but will be included prior to finishing the software). These tests stimulate retrieval of previously stored and learned information, which is known to strengthen the memory of that information [31]. Further, pre-testing is effective in potentiating subsequent learning even when students answer very few of the questions correctly, both by directing subsequent attention and also by activating subsequent encoding of information [32]. The exercises themselves qualify as tests in this respect, and providing frequent feedback on right and wrong answers (with detailed explanations, where requested) is known to be a very effective method to enhance learning [32]. Further, the testing can help improve students' metacognition regarding what they do and don't know well [33]. Frequent experience with low-stakes testing can also reduce anxiety on subsequent high-stakes tests [34].

Our system also aims to minimize *undesirable* learning difficulties, such as extraneous cognitive load [2]. For example, students may initially have difficulty visualizing the ways in which wires interconnect various circuit elements to form nodes. We provide color coding of the nodes to scaffold the initial learning of this task, then withdraw that support at higher levels where students have already practiced this skill and are advancing to mastery of the subject. Further, we color code individual equation terms to help students easily match the structure (terms) of each equation to the corresponding branch current or voltage. We also color code sets of elements in series and parallel when presenting those concepts. These pedagogical devices help students focus on the core concepts (the germane cognitive load).

The Circuit Tutor system supports the use of active learning even during the initial presentation of the concepts in the tutorials that precede the exercises for each topic. We present small amounts of textual material, alternating with multiple choice and similar types of questions that engage the student in learning the material more effectively than traditional textbooks containing large sections of text and noninteractive examples. In this respect, our system is similar to the successful interactive electronic textbooks that have recently been developed in other domains [35]. Instructors can view student progress and answers on these tutorials from a web-based instructor interface, and students are required to complete the tutorials prior to being able to access the examples and exercises.

III. CIRCUIT GENERATION AND SOLUTION ENGINE

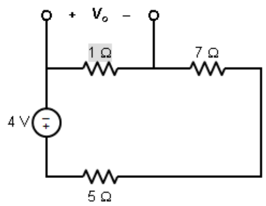
The three-stage process used in our system to create random circuit topologies that are both soluble and similar to the "typical" problems found in linear circuit textbooks has been described in detail elsewhere [36-42], along with the criteria used to define a "good" problem. Automated solution methods such as node and mesh analysis (using concepts such as supernodes and supermeshes) and simplification steps such as combining elements in series and parallel have also been described [36-42]. Here, we focus on some of the additional automated solution methods we have implemented more recently. All of these methods are analytical in their approach and use approaches typically taught in beginning textbooks, as

(a)

Compute the following 2 quantities for this circuit:

V_o; P_{diss} (1 Ω)

Here, P_{diss} (1 Ω) denotes the power dissipated in the gray–labeled 1 Ω resistor.



Sought variable equations:

In a series circuit, the voltage provided by the source is divided among the resistances.
The voltage across each resistance is the source voltage multiplied by the ratio of the resistance in question to the sum of all the resistances in series.
Because the polarities of the voltage source and the sought voltage have opposite senses (the positive side of the source is connected to the negative side of the sought voltage), the sought voltage has a negative sign in this equation.

$$V_o = -4\text{ V}\,\frac{1\ \Omega}{1\ \Omega + 5\ \Omega + 7\ \Omega} = -0.308\text{ V}$$

The power dissipated in this resistor is P = VI = V²/R, where V is the sought voltage V_o we already computed above.

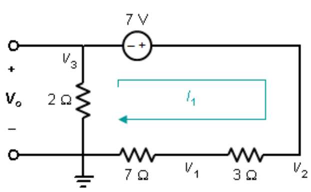
$$P_{diss}\,(1\ \Omega) = \frac{(V_o)^2}{1\ \Omega} = 0.0947\text{ W}$$

(b)

Compute the following 2 quantities for this circuit:

V_o; V_{13}

V_{mn} is the voltage difference $V_m - V_n$, where m and n are node indices.



Sought variable equations:

Given that we have been asked to find a non–branch voltage in this circuit, we cannot simply use the normal voltage division formula. Instead, we apply KVL around the closed loop to solve for the unknown current I_1, which we define as that traveling in a clockwise direction around the circuit as indicated.
We can then use that current in a second application of KVL to find the desired non–branch voltage(s).

To do this, we add the voltage DROPS across each element, traveling in a clockwise direction.
As this direction is the same as that of I_1, we are automatically using the passive sign convention for each passive element, so that those terms have positive coefficients.
Further, the voltage drop across each voltage source we encounter is just the value of the source if we encounter its positive side first, or the negative of its value if we encounter its negative side first:

$$I_1(2\ \Omega) - 7\text{ V} + I_1(3\ \Omega) + I_1(7\ \Omega) = 0$$

Solving this equation yields $I_1 = 0.583$ A. Next, we use that value to find each desired quantity:

Using the passive sign convention, the voltage V_o across the 2 Ω resistance is just that resistance multiplied by the net current entering its positive side. This current is just the negative of mesh current I_1, because I_1 enters the negative side of voltage V_o.

$$V_o = -I_1(2\ \Omega) = -1.17\text{ V}$$

Finding the non–branch voltage V_{13} requires that we sum all voltage rises from node 3 to node 1, using a path that does NOT go through any DC capacitors or current sources, whose voltages would be unknown.
Each voltage source along this path (if any) contributes a positive voltage rise if we encounter its negative terminal first, or a negative voltage "rise" (really a drop) if we encounter its positive terminal first.
The voltage rise across each resistance is I_1 times that resistance if the direction of I_1 is opposite to our direction of travel along the path, as the passive sign convention implies a positive rise in that case, or negative I_1 times that resistance if I_1 is directed along the chosen path.
We choose to do this using the path where the resulting expression will be the simplest:

$$V_{13} = 7\text{ V} - I_1(3\ \Omega) = 5.25\text{ V}$$

Fig. 1. Automatically generated single loop analysis examples, showing the computer-generated equations and solutions. (a) (Top) Simple case where the normal voltage division formula can be used. (b) (Bottom) Case where KVL must be used to find a non-branch voltage.

opposed to the numerical (modified nodal analysis) approaches taken by circuit simulation software such as PSPICE.

One very important method is voltage and current division (or more generally, single loop and single node-pair analysis methods). These approaches are essentially limiting cases of general mesh and nodal analysis for simple circuits, but can use specific formulas that should be familiar to all circuit analysts. Such methods can often be applied even when the circuits do not strictly meet the criteria of being single loop or single node-pair, as we have discussed elsewhere [43]. They are also very important as the methods of choice when using superposition or when doing many transient analyses. Automatic generation of solutions using these methods can be surprisingly complicated when considering all possible cases. Unusual cases include those involving one or more dependent sources (which are introduced in some textbooks for this type of circuit, even though they are necessarily equivalent to resistors or to negative resistors in this case); single loop cases involving a current source or single node-pair cases involving a voltage source (which require application of Ohm's law rather than the usual voltage or current division formulas); and cases with a variety of sought quantities (i.e., unknowns to be found by the student), such as branch currents, branch voltages, branch powers, and "non-branch voltages" (voltages not appearing across a single element in the single-loop case). Many of these cases require (or are more efficiently addressed by) explicit use of Kirchoff's voltage law (KVL) or Kirchoff's current law (KCL), in place of the "usual" voltage/current division formulas. Also, the system must accept a wide variety of possible correct forms of the answers, particularly for sought powers, which can often be written many different ways. The expressions for sought non-branch voltages involve a sum of terms involving voltage drops across several circuit elements and must be written using KVL along one of two possible paths connecting the two nodes whose voltage difference is sought.

We have now completed the very complex code required to handle all these different situations efficiently and to accept a wide variety of valid forms for the student answers. The answers (as in the case of node or mesh analysis) are formed using a palette of terms in standard form where the student is required to select the appropriate terms in a given case and fill in all the blanks in those terms with appropriate values. This code also provides much more detailed explanations of the computer-generated equations (in examples or worked solutions) than is normally done in node or mesh analysis, because students studying this topic normally do so prior to learning node or mesh analysis and are at an earlier stage in developing their understanding of circuit principles. All of the above code can handle both DC and AC (phasor analysis) circuits equally well, treating inductors as short circuits and capacitors as open circuits in the DC case (as may be needed for transient analysis). Example solutions are shown in Figs. 1(a) and (b), respectively, for voltage division in cases where the traditional voltage division formula suffices and where KVL is instead needed explicitly.

We have further developed the ability to solve problems involving superposition using the above methods. The student will use our interactive circuit editor [39-41] to turn "off" all but one of the independent voltage or current sources in such cases prior to carrying out the solution. In cases where the resulting circuit must be presimplified prior to using single node-pair or single loop methods (simplifiable, voltage or current-splittable, or iteratively solvable cases as defined in Ref. [43]), the student will use the interactive editor to carry out the required operations on the circuit.

Problem

Given a transfer function

$$\mathbf{H}(j\omega) = \frac{400j\omega}{(j\omega)^2 + 58j\omega + 400}.$$

A. Find the limits of $\mathbf{H}(j\omega)$ when $\omega \to 0$ and $\omega \to \infty$.

B. Identify the type and order of the filter corresponding to the above transfer function.

C. Draw a Bode magnitude plot for the above transfer function.

Solution to Part A:

$$\lim_{\omega\to 0} \mathbf{H}(j\omega) = \frac{400 \cdot 0}{0^2 + 58 \cdot 0 + 400} = 0,$$

$$\lim_{\omega\to\infty} \mathbf{H}(j\omega) = \lim_{\omega\to\infty} \frac{400j\omega}{(j\omega)^2 + \cancel{58j\omega} + \cancel{400}} = \lim_{\omega\to\infty} \frac{400j\omega}{(j\omega)^2} = \lim_{\omega\to\infty} \frac{400}{j\omega} = \frac{400}{\infty} = 0.$$

Solution to Part B:

The magnitude is attenuated at lower and higher frequencies. Further examination below will show this is a band-pass filter. We can verify this conclusion after we obtain the Bode plot of the transfer function.

The order of a filter is simply the number of poles in the transfer function. This filter has two poles, so it is a second order filter.

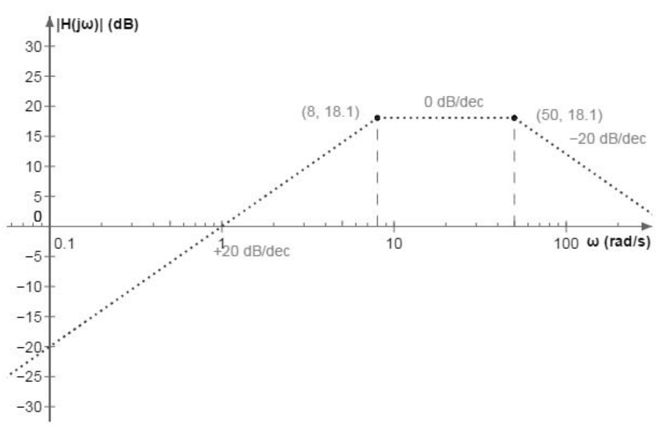
(Large portions omitted here)

In summary,

Break Frequency (rad/s)	-	8	50
Type	zero at origin	simple pole	simple pole
Slope to Right of Breakpoint (dB/dec)	+20	0	−20
Slope Change (dB/dec)	-	−20	−20
Magnitude at Breakpoint (dB)	-	18.1	18.1

The slopes in this table are obtained from the coefficients of log ω in equation 3. The slope changes in this table are the changes in the slopes of the asymptotic approximations going from the left side of a breakpoint to its right side. Note that a simple zero always produces a slope change of +20 dB/dec, and a simple pole always produces a slope change of −20 dB/dec. The magnitudes at the breakpoints are computed from the intercepts above.

Using this table, we can sketch the asymptototic approximation to the Bode magnitude plot from 0 to ∞ as shown below. Specifically, we plot a point for the magnitude of $|\mathbf{H}(j\omega)|$ at each break frequency and connect those points by straight lines. Then we use the slopes to continue the sketch in the end regions.



***Step 6*: Sketch the exact curve of $|\mathbf{H}(j\omega)|$.**

Fig. 2. Portions of a web-based example for a problem where the student is asked to draw the Bode plot for a given transfer function. Large portions of the explanation are omitted for brevity.

IV. Web-Based Modules

Many of the newer portions of our system are entirely web-based, which facilitates easy student access. Two tutorials address the sketching of waveforms as a function of time. The first relates basic electrical quantities such as charge, voltage, current, power, and energy, and is usually covered near the start of the course. The second relates quantities involving capacitors and inductors, such as charge, magnetic flux, voltage, and current, and is typically covered when first introducing reactive elements in the middle of the course. In both cases, the computer randomly generates a waveform for one of the relevant quantities as a function of time, using piecewise functions built from constants, ramps, sinusoids, and so forth, and asks the student to sketch a different, related quantity. These problems may involve simple multiplication (as when relating capacitor charge to its voltage, for example), differentiation (as when finding inductor voltage from its current), or integration (as when finding capacitor voltage from its current). In all cases a variety of metric prefixes is used to promote familiarity with them. The student sketch is automatically evaluated for correctness, and the student can as usual view fully worked examples or "give up" and view the fully explained solution to the problem they are working on at any time without penalty. They then receive a new problem of the same type.

Another recently developed module asks students to sketch Bode plots for a given transfer function, and also to determine what type of filter is represented by that function. Every step of the process is explained in great detail, including all of the mathematical calculations and approximations involved, so that even students with relatively weak mathematical backgrounds should be able to follow the argument. An example of this type is shown in Fig. 2 (though large portions of the explanation are omitted there for brevity). The asymptotic form of the Bode plot will be determined by the student by approximating the transfer function appropriately at each break frequency, then connecting those points and using the slopes in the end regions to continue the plot beyond the break points. Each step in the student's work will be evaluated to ensure the correctness of their procedure.

Another web-based module uses a template-based interface to construct both direct and inverse Laplace transforms, the latter using the partial fraction method in combination with tables of transform pairs. Future extensions are planned to cover Fourier analysis also.

V. Evaluation of Student Learning

In previous work, we performed two randomized, controlled trials to assess student learning using our system in comparison to prior approaches. In the first, we compared learning in a laboratory setting using student volunteers who were randomly assigned either to use our software for one hour on one qualitative and one quantitative topic (identification of elements in series and parallel, and writing node equations for a given circuit, respectively) in comparison to doing traditional paper homework problems on the same topics [37, 38]. A statistically significant advantage ($p < 0.05$) was found for our system on a post-test with an effect size (Cohen *d*-value) of 1.21 pooled standard deviations (σ). A survey used to assess the motivational impact of the software found a significant advantage for our system with an effect size of $d = 0.91\ \sigma$.

A second study was carried out in Fall 2014 in a classroom-based setting, where students were randomly assigned in one section of the EEE 202 (Circuits I) course at ASU to use either Circuit Tutor or a widely-used, commercial publisher-based homework system (denoted System X in the following) for DC nodal analysis, and the opposite system for DC mesh analysis [40, 41]. The problems in System X were selected to be very similar in type and number to those used in the Circuit Tutor exercises, though students may have to complete additional problems in the latter case if they make too many errors while doing the minimum required problem set. Significantly better homework scores were achieved on the Circuit Tutor exercises ($p < 0.008$ with an effect size $d = 0.41\sigma$). After completing the required work, which counted towards their homework grade in the course, students were given the opportunity to use the system they were not required to use for each topic for additional practice (but no additional credit of any kind). Fully 32 or 34% of the students assigned to use System X for a given topic then voluntarily completed at least one level of the Circuit Tutor exercises on that topic, but *no* students assigned to use Circuit Tutor voluntarily completed any additional work in System X. This strong preference was taken as a clear indication of student opinions on the two systems. However, the large crossover contamination that was permitted in this experiment did not permit the administration of an effective post-test to discern differences in student learning.

The experiment of Fall 2014 was therefore repeated in a different section of EEE 202 in Fall 2015, but with the addition of an in-class proctored quiz (post-test) administered on the due date of the homework (prior to any students being allowed to use the system they were not assigned to use on a given topic). The ~45 minute paper post-test was the same for all students and covered both nodal and mesh analysis. No pre-test was employed, but random assignment of the ~70 students should yield similar average ability levels in both groups. Further, the overall scores of Groups A and B for the entire course (including many other topics) were very similar (68.5% vs. 72.0%, respectively), as well as their scores on the DIRECT 1.0 concept inventory [44] covering basic electricity given at the start of class (53.2% and 54.8%, respectively). Group A was required to use Circuit Tutor for DC nodal analysis (two tutorials, covering both the formulation and solution of nodal analysis equations), and System X for DC mesh analysis. Group B was required to do the reverse (use Circuit Tutor for mesh analysis and System X for nodal analysis). In System X, problems were selected to be very comparable to the typical number and type of problems required in Circuit Tutor, and students were allotted four attempts to input the correct final answer. The problems in System X are algorithmic, where each student uses the same circuit diagram, but one or a few element values are randomly changed. Only the final numerical value of the "sought quantity" is evaluated for correctness. The correct solution (to a version with the same element values as the textbook version) is shown if four attempts are failed. All of the above homework was assigned following the usual lectures and assigned readings on the relevant material. Grading of the post-test was done by the instructor in a "blind" fashion without knowing the group assignment of the students being graded. In addition to the post-test, all students were requested to complete an anonymous survey (administered through the Blackboard learning management system) that asked them to compare the relative effectiveness of both systems for learning the material and also which system they preferred using.

The results of the post-test for both groups are shown in Table I. For nodal analysis, the Circuit Tutor users (Group A) had a statistically significant higher average score [$t(64) = 3.09$, $p < 0.05$] with a large effect size of 0.72σ. In the case of mesh analysis, both groups did relatively well and the difference of mean scores was not statistically significant [$t(64) = 0.88$, $p = 0.38$]. The latter result may reflect what we have found to be the fundamentally easier nature of mesh analysis in comparison to nodal analysis. This difference may be due to the relative ease of visualizing voltage drops around a closed loop (mesh or supermesh) in comparison to visualizing the currents leaving a closed surface (node or supernode) in nodal analysis. The easier nature of this topic may make it less sensitive to the instructional treatment. There was however a very pronounced preference of students for Circuit Tutor over System X (89% vs. 6%, respectively, with the remaining students favoring both systems equally). Students also felt strongly that Circuit Tutor did a better job of teaching them the material than System X (94% vs. 3%, respectively, with the remaining students rating both systems equally). The survey ratings include both students who used Circuit Tutor for nodal analysis and those who used it for mesh analysis. The average scores on the homework assignment itself were also higher for the Circuit Tutor students (79%, vs. 69% for System X students).

Qualitative comments were solicited in response to the question "Please discuss why you preferred the system that you did, and the relative merits of the two systems at teaching you the subject of node or mesh analysis." The 35 responses (51% response rate, averaging 77 words long) were analyzed by dissecting the comments into 45 specific statements, with each response being coded as containing anywhere from one to ten of those statements (average of 3.9). The statements were constructed by the first author and categorized into preliminary categories, and Dr. Robinson then reviewed and refined the statements into nine final categories. The statement types were classified as favorable to Circuit Tutor over System X (76%), favorable to System X over Circuit Tutor (20%), neutral (2%), or unclear (2%). The frequency of each statement among all the responses was then counted, and we found that 88% of the statement occurrences were favorable to Circuit Tutor, 10% were favorable to System X, 1% were neutral and 1% were unclear. A breakdown of favorable responses by category is shown in Table II. The qualitative responses therefore align very well with the responses to the quantitative responses to the multiple-choice questions.

Table I. Randomized Classroom-Based Comparison of Posttest Scores for Circuit Tutor vs. Publisher System X.

Experimental Group	Avg. Post-Test Score % (std. dev.)
Circuit Tutor—Nodal Analysis	72% (24%)
System X—Nodal Analysis	49% (33%)
Circuit Tutor—Mesh Analysis	71% (25%)
System X—Mesh Analysis	65% (31%)

By far the most common statement (in our paraphrasing) was "Circuit Tutor provides more detailed guidance and teaches me better than [System X] and/or provides better explanations" with 25 instances. The five next most common ones were "Circuit Tutor allows me to repeat problems until I get the right answer, with solutions given" (9 instances), "[System X] does not provide examples or learning assistance prior to working problems" (8), "Circuit Tutor is much better than [System X] or should be used in preference to [System X] in the future or is strongly preferred" (7), "[System X] did not help me learn or did not give me a refresher on how to do what I needed to do" (7), and "[System X] does not tell me what I did wrong, only that the final answer is wrong" (6) [numbers in parentheses are number of instances in each case]. The four most common statements favorable to System X (but uncommon overall) were "Circuit Tutor makes the problems too easy and gives too much guidance" (2 instances), "[System X] is better because it is a little bit more challenging or more like exam problems" (2), "[System X] provides useful links to the textbook" (2), and "[System X] has some helpful problem-solving videos" (2). Verbatim examples of student comments are shown in Table III. They were selected as ones including the five most common statements made by students.

Table II. Responses to Survey Comparing Circuit Tutor to a Publisher-Based System

Category	Responses	Favorable*	Unfavorable*
1. Overall opinions	9	89%	0%
2. Effect on motivation or attitude	13	100%	0%
3. Appropriate level of difficulty and coverage	10	60%	40%
4. Facilitation of learning	54	96%	4%
5. Repeated testing/retrieval practice/mastery	12	100%	0%
6. Providing useful examples	16	88%	13%
7. Providing useful feedback	10	90%	10%
8. Technical problems and user interface	9	33%	44%
9. System cost	2	100%	0%
Combined	135	88%	10%

*to Circuit Tutor, in comparison to System X. Percentages are those of all statements by respondents. Remaining responses were neutral or unclear.

The least favorable categories in Table II were those related to appropriate level of difficulty and coverage, and technical problems and user interface. The former complaints were mostly that Circuit Tutor made the problems too easy by providing a lot of guidance, and the latter were mostly about the more complicated user interface. However, a system that requires students to enter many different forms of input inherently requires a less consistent and more variable

Table III. Sample Verbatim Student Comments from the Comparative Survey of Circuit Tutor and System X.

- Simple, Circuit Tutor actually gives you examples and shows you want to do before making you do it. [System X] does not.
- Circuit tutor walks you through problems clearly and one step at a time. It also allows you infinite attempts so you can attempt the problem repeatedly with less stress about losing points. Circuit tutor's explanations for problems are also easier to follow.
- I liked Circuit Tutor more because I could do a ton of problems. I liked that even if I couldn't figure it out, I could 'give up' and it would thoroughly explain how to do everything so I could understand what I did wrong and then do a new problem and try to get that right. I seem to retain more of the content when I am doing this one. I have trouble with [System X] because, if I have trouble with a problem, the hints do not explain what I am doing wrong. It's really frustrating because I could be 2 or 3 wrong attempts in and I do not know what I'm doing wrong.
- I preferred Circuit Tutor because it was more forgiving in the aspect of not just showing that your answer was wrong like [System X], it helped guide you to the solution. I felt it was a more effective learning tool, while [System X] would be better as a quiz tool after using Circuit Tutor. When it came to the quiz I felt much more confident on the node questions vs the mesh questions because of Circuit Tutor. I plan to use Circuit Tutor some more to prepare for the upcoming test.
- Circuit Tutor is far better. [System X] is not only more difficult, but only allows 4 attempts. [System X] discourages me while Circuit Tutor teaches me.
- I liked Circuit Tutor more because Circuit Tutor helped me learn, while [System X] simply tested my knowledge.

interface than a commercial system that primarily accepts only numerical or multiple choice answers. Overall, students still preferred our system due its step-based nature.

Another, independent evaluation was carried out in Fall 2014 at the University of Notre Dame in EE 20224 (Introduction to Electrical Engineering). Random assignment was not used in this case. One (experimental) section of the course was required to complete the Series-Parallel and Series-Parallel with Terminals tutorial exercises in Circuit Tutor (covering identification of elements in series and parallel, with our without the presence of a set of terminals connected to an ideal voltmeter, an arbitrary subcircuit, or an ohmmeter). A different (control) section was instead assigned to read the textbook discussion of that topic, do an assessment problem from the textbook, and complete a paper-based exercise where they were asked to identify series and parallel elements in about 20 different circuit problems selected from the book. Both groups took a pre-test and a post-test of similar forms (with each of the two forms randomly assigned as either pre-test or post-test to average out any difference in difficulty). Altogether the experimental group spent about 1.75 hours on the subject (including the pre- and post-tests) and the control group spent about 1.5 hours including the tests. A one-way analysis of covariance was carried out on the post-test scores using the pre-test scores as a covariate. A statistically significant improvement was found for the experimental (Circuit Tutor) group, who had an adjusted mean score of 36.68 compared to that of the control group, 30.49, with $F(1.62) = 16.76$, MSE = 36.3, and $p < 0.001$. The effect size was $d = 0.97\ \sigma$, a large effect. A similar experiment involving the nodal and mesh analysis tutorials did not however provide a reliable comparison because of large differences in the corresponding pre-test scores between the two sections.

VI. Usage Statistics and Surveys

As of Spring 2016, our system has been used by over 2860 students in a total of 71 class sections taught by 36 different instructors at ten different colleges and universities, including Arizona State University, University of Notre Dame, University of the Pacific, Morgan State University, Auburn University, Messiah College, North Carolina A&T State University, University of Virginia, South Mountain Community College, Chandler-Gilbert Community College, and Glendale Community College. These institutions span the range from medium size to large public universities, a primarily bachelor-level private university, a large, elite private university, two historically black universities, and several community colleges. The software has therefore been found to be effective and well received in a wide variety of settings and with widely varying student populations.

The software itself is currently composed of 18 different tutorials covering topics ranging from identifying elements in series and parallel; sketching waveforms for current, voltage, power, energy, and related quantities as a function of time based on a given waveform for a different quantity; combining resistors, inductors, capacitors, and general impedances in series and parallel (including the computation of AC impedances from element values); writing and carrying out a complete solution of both nodal and mesh analysis equations for both DC and AC (phasor) circuits; finding both direct and inverse Laplace transforms; and sketching Bode plots and identifying filter types from given transfer functions. Many other tutorials are in active development, and basic capabilities have been established for writing voltage and current division equations (single loop and single node-pair analysis) as described earlier, circuit analysis for transient circuits using reactive elements in steady state, development of Thévenin and Norton equivalent circuits, and superposition analysis. The goal is to cover all major topics in a typical two-semester linear circuit analysis course.

Student satisfaction is assessed in our system using a short, two-question survey upon completion of each individual tutorial, and more comprehensively by a 12 multiple-choice question survey (with 3 open-ended questions) at the end of each semester where the software is used. The short surveys simply ask whether the software was "very useful," "somewhat useful," "not very useful," or "a waste of time" for learning the material in question, and solicit any open-ended comments about the tutorial in question. The percentage of favorable ("very useful" or "somewhat useful") responses has varied in the range from about 92-96%, with "very useful" responses ranging from about 65-74%. These results have been consistent across institutions as well, with favorable ratings of 92% at ASU, 94% at Notre Dame, 95% at the University of the Pacific, 97% at Morgan State University, and 95% at Messiah College, for example. It is clear that students at a wide variety of institutions have favorable views of the software. The end-of-semester surveys also yielded consistently favorable ratings on a four-point Likert scale, with values of 79%, 91%, 65%, 76%, and 87%, respectively, for the same five institutions listed above. The somewhat lower rating for the University of the Pacific may be due to the students having used the software in addition to several other types of exercises on the same topics as well, in which case it may be viewed as partially redundant. Sample qualitative responses have been given elsewhere [37-41]. It is particularly remarkable when students use the word "fun" in their comments to describe our software (e.g., nine times in one recent semester's comments), which is virtually never heard when describing conventional homework assignments!

VII. Conclusions

A step-based tutorial system is being developed for linear circuit analysis that uniquely features automated problem and solution generation, and which accepts and automatically evaluates a wide range of student inputs from equations to Bode plots to waveform sketches to re-drawn circuit diagrams. The system is built on the principle of using "*engaged examples*," where students are provided completely explained solutions to problems they have already tried to solve whenever they need them. Wide usage by 2860 students has been achieved at 10 different institutions of widely varying characteristics. A total of 18 different tutorials are available with more in development. Several controlled, randomized evaluations of student learning in both laboratory and classroom settings in comparison to both traditional paper-based homework and a commercial publisher-based homework system have shown statistically significant learning improvements in most cases, varying from 0.72 to 1.21σ improvements in post-test performance in trials involving 6 of the 18 tutorials to date. Student responses have generally been quite favorable, and in particular they rate our system as better at promoting learning than a commercial publisher's homework system by a margin of 94% to 3%. This system is currently available for those would like to use it in their classes (contact the first author directly for an access code).

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