Advances in Step-Based Tutoring for Linear Circuit Analysis and Comprehensive Evaluation

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Abstract

Step-based tutoring consists in breaking down complicated problem-solving procedures into individual steps whose inputs can be immediately evaluated to promote effective student learning. Here, recent progress on the extension of a step-based tutoring for linear circuit analysis to cover new topics requiring complex, multi-step solution procedures is described. These topics include first and second-order transient problems solved using classical differential equation approaches. Students use an interactive circuit editor to modify the circuit appropriately for each step of the analysis, followed by writing and solving equations using methods of their choice as appropriate. Initial work on Laplace transform-based circuit analysis is also discussed. Detailed feedback is supplied at each step along with fully worked examples, supporting introductory multiple-choice tutorials and YouTube videos, and a full record of the student's work is created in a PDF document for later study and review. Further, results of a comprehensive independent evaluation involving both quantitative and qualitative analysis and users across four participating institutions are discussed. Overall, students had very favorable experiences using the step-based system across Fall 2020 and Spring 2021. At least 48% of students in the Fall 2020 semester and 60% of students in the Spring 2021 semester agreed or strongly agreed with all survey questions about positive features of the system. Those who had used the step-based system and the commercial MasteringEngineering system preferred the former by 69% to 12% margins in surveys. Instructors were further surveyed and 86% would recommend the system to others.

1. Introduction

Introductory circuit analysis forms a key gateway course for electrical engineers and is also frequently a required course for many other engineering majors. Therefore, success in this course is crucial for retention of engineers and considerable research has been done to improve it, as reviewed for example by Reagan et al. [1], though it was found to be of variable quality. Circuits are complex systems to understand because of their highly interconnected behavior, where each element typically affects all other portions of the circuit. This topic can therefore pose a high intrinsic cognitive load on students, potentially overwhelming their working memories and impeding the necessary formation of schemas in long-term memory [2, 3].

For students to learn effectively in such courses, active learning through problem solving is essential. Traditionally, paper homework was assigned, but students may not receive feedback on the correctness of their work until it is manually graded and returned perhaps a week later, at which point they have already gone on to other topics. Such manual grading may not always be accurate or thorough and is expensive. Automated grading is therefore sometimes used, often involving problems whose numerical parameters are varied to some extent. However, in most cases such systems are answer-based, evaluating only the final answer that often requires many complex steps to obtain. In such cases, there may be no way to guarantee that students actually used the technique their instructor wanted them to use to solve the problem, as opposed to an alternate method.

Systems such as WeBWorK and LON-CAPA or Cengage's WebAssign can be used to create such problems, though their application in engineering has been limited [4, 5]. Special purpose systems have also been used for assessment, which were again generally answer-based [6-8]. Such approaches have however either not led to any learning gains [5], were reported to increase examination passing rates but without any detailed description of the experiment or tests of statistical significance [6], did not assess impact on student learning in any controlled way [8], or did not assess learning gains on the topic of circuit analysis [7]. The most commonly used systems are likely those provided by commercial publishers as support for specific textbooks, such as Pearson's MasteringEngineering, Wiley's WileyPLUS, McGraw-Hill's Connect, etc. Such systems are generally answer-based, though in a limited number of cases they may request some intermediate steps. Little assessment data on student learning in linear circuits using such tools has however been reported.

A more sophisticated though complex approach is step-based learning, where every major step of a student's work is accepted by the computer and immediately evaluated, giving more frequent feedback. Such systems in general have been shown to produce learning gains of 0.76σ comparable to those achieved by very expensive expert tutoring (0.79σ), and significantly better than those usually found for answer-based systems (0.31σ) [9]. A system of this type called Circuit Tutor has been developed and assessed in several prior studies [10-20]. In controlled, randomized experiments, specific modules resulted in a 1.21σ improvement in post-test scores in a lab-based study comparing it to paper homework on series-parallel relationships and nodal analysis [11, 12]; a 0.41σ improvement in homework scores when compared to WileyPLUS in a classroom-based study [15]; a 0.72σ improvement in post-test scores on nodal analysis in a classroom-based study comparing to WileyPLUS, but no statistically significant difference on mesh analysis [16, 17]; and a 0.97σ improvement in post-test scores (using pre-test scores as a covariate) in a classroom-based experiment comparing to paper-based exercises on series-parallel relationships [17]. All quoted effect sizes were statistically significant ($p < 0.05$). On the complex topics of DC superposition and DC source transformations, no statistically significant difference was found in a limited posttest compared to WileyPLUS in Spring 2019 [18, 19]. In a similar experiment in Fall 2019 on DC superposition, DC source transformations, and DC Thévenin/Norton equivalent circuits, an improvement of 0.64σ on a post-test compared to paper homework was found in one class section, but there was no statistically significant difference in another section [19]. In all experiments, student surveys indicated a strong preference for Circuit Tutor over both WileyPLUS and paper homework [11, 12, 15-19].

Based on the positive results achieved previously, further extension of this system to the remaining topics in a typical introductory linear circuits course or sequence appears to be desirable. To date the system covers identification of series and parallel elements, including cases with terminals; series and parallel simplification of resistors, inductors, capacitors, and general impedances; analysis of single loop and single node-pair circuits including voltage and current dividers; nodal and mesh analysis in both DC and AC (phasor analysis) cases including supernodes, supermeshes, and dependent sources; superposition, source transformation, and Thévenin/Norton equivalent circuits for both DC and AC circuits; construction of Bode plots and identification of filter types from transfer functions; sketching waveforms corresponding to a given one, such as finding capacitor voltage given its current or power given energy (currently undergoing revision, however); and the mathematics of direct and inverse Laplace transforms. Additional topics that remain to be added include first and second-order transient analysis using

differential equations, operational amplifier circuits, Laplace transform circuit analysis, mutual inductance and transformers, AC power, Fourier analysis, three-phase circuits, and possibly two-port circuits. Here, the development of modules covering first and second-order transient analysis of switched circuits using differential equations is discussed, along with preliminary work on Laplace transform circuit analysis.

Independent evaluation of the implementation of Circuit Tutor across four participating institutions including Arizona State University (ASU), Florida Agricultural and Mechanical University/Florida State University (FAMU/FSU), Morgan State University (MSU), and University of Texas at El Paso (UTEP) is also discussed based on both quantitative and qualitative analysis and surveys of both students and instructors. Various features of the system were assessed by both students and instructors.

2. Overview of the system

Circuit Tutor is based on random problem generation using a three-step algorithm, where both topologies and element values are randomly selected according to preset specifications [10, 11]. The circuits are guaranteed to be solvable and meet a variety of criteria making them "good" problems. The system features both fully worked and explained examples as well as problems that are isomorphic to the examples, both being generated by the same engine. It differs strongly from systems such as PSPICE in that it uses the same methods typically taught to students in elementary courses, rather than numerical approaches based on modified nodal analysis. It has the ability to simplify circuits automatically by combining elements in series and parallel and by source transformations, and by eliminating irrelevant portions of a circuit that are either hinged or voltage-splittable or current-splittable, as discussed in [21]. It also uses the idea of sought variable transformations [18, 19] to permit simplification of circuits in series or parallel without losing the desired unknown, called the sought variable. Some similar random problem generation systems have been developed by other workers [22-26], but have either not been fully developed [22, 23, 26] or have not demonstrated clear learning gains [24, 25]. The system uses carefully graded levels of difficulty, starting with easy problems to build confidence.

Specialized interfaces are used to accept and evaluate each stage of a student's work. A scaffolded template-based entry system is used for equations, where appropriate term types for a given situation are offered. A special waveform sketching interface is used to draw piecewise waveforms as functions of time, and another interface is used to draw Bode plots. An interactive on-screen circuit editor with several restricted editing modes as well as an unrestricted editing mode is used to permit circuit modification and give immediate feedback on correctness of same. Forms are used for entry of simplified equations and matrices numerical answers, and multiple-choice questions.

Students are never penalized for wrong answers, except that making more than a specified number of errors on a given step can result in loss of credit for the problem. In that case, they can either complete the problem for no credit or give up and be shown a complete, fully explained solution. Then they are given another problem of the same type and difficulty (with a new topology and element values) and can earn full credit as long as they complete the required number of problems without excessive errors at each level. Mastery learning is a key component of the system. Copying from other students or a solution manual is impossible as every student

gets completely different problems (of comparable difficulty), so academic integrity is strongly encouraged. Further, students have access to an unlimited supply of both fully worked examples and as many new problems as they need to master the topic. Congratulatory sounds are played on correct answers and level completion and certificates are awarded for completed games, to support a game-like atmosphere.

Pedagogical features such as color coding of nodes and mesh currents are also used to help students understand the structure of the circuit, and equation terms are color-coded to match the corresponding current arrow or voltage drop on the diagram. Interactive introductory multiple-choice tutorials are provided on every topic in the system, and emphasis is placed on approaches to topics like series connections and mesh analysis that are consistent with duality, a fundamental organizing principle of the subject [27]. Heavy emphasis is given to conceptual issues, unlike most textbooks in this field [28]. A total of 80 help videos are available on YouTube [29] and linked into the program, showing how to use the program interfaces and how to solve each type of problem in the system, including all details of relevant algebra, complex number calculations on calculators, etc. A complete record or transcript of student work in the system showing both correct and incorrect steps taken on each problem is available to students in a PDF format for studying and review, the lack of which is an important disadvantage of other online homework systems. An extensive set of administrative tools including a gradebook and graphical instructor dashboard to view overall student progress is available. These tools allow the instructor to assign different grade weights and requirements to different modules.

3. New modules on transient circuits

Solving first and second-order transient problems in switched circuits using classical (non-Laplace-transform) differential equation approaches is a standard textbook topic [30-34]. These types of problems are typically among the most challenging and complex for students to complete in introductory courses, in the first author's experience, due to the numerous steps that are required. In first-order circuits, transient waveforms always have the form $x(t) = A \exp(-t/\tau) + B$, where $x(0^+) = A+B$ and $x(\infty) = B$, where $x(t)$ is any voltage or current in the circuit and $\tau = R_{Th}C$ or $\tau = L/R_{Th}$ for RC and RL circuits, respectively [30]. Here, R_{Th} is the Thévenin equivalent resistance "seen" from the terminals of the reactive element for $t > 0$ after de-activating all independent sources, and the switch is assumed to operate at $t = 0$.

Solving a specific problem therefore requires finding the three values $x(0^+)$, $x(\infty)$, and R_{Th}, where the specific "sought variable" x is specified in the problem statement. The value of $x(0^+)$ (immediately after the switch action) $= x(0^-)$ (immediately before the switch action) if x is the current of the inductor or the voltage of the capacitor, as those quantities cannot change instantaneously. If it is some other value, such as a resistor voltage or current, the circuit must be solved explicitly for $x(0^+)$ after replacing the inductor by an independent current source of value $i_L(0^-)$ or by replacing the capacitor by an independent voltage source of value $v_C(0^-)$ as appropriate [30].

The process used in Circuit Tutor is to present the original circuit with a switch and allow the student to select the time at which they wish to solve it (0^-, 0^+, ∞, or $t > 0$ to find R_{Th}). They then enter the circuit editor in a "reconfiguration mode," in which they alter the circuit in ways

Compute the following quantity for this circuit:
$i_L(0^-)$

Reconfigure circuit for analysis at time $t = 0^-$
(Do not simplify in this mode.)

Circuit Editing (Ckt. Reconfiguration Mode)   x

In this mode, you need to make the changes necessary to analyze this circuit at the desired time. Once you have finished, just click "Done Reconfiguring Ckt." You will then have the option to enter simplification mode to simplify the circuit. You can not do simplification while in this mode.

Select   Add New   Reverse Polarity   Stretch

Create or Transform   Compress

Testing Mode   Shift

Done Reconfiguring Ckt.   Help

Restore Circuit   Video Help (Level #1)

Sounds   Freeze Dialog Boxes

1 Ω
9 Ω
7 V
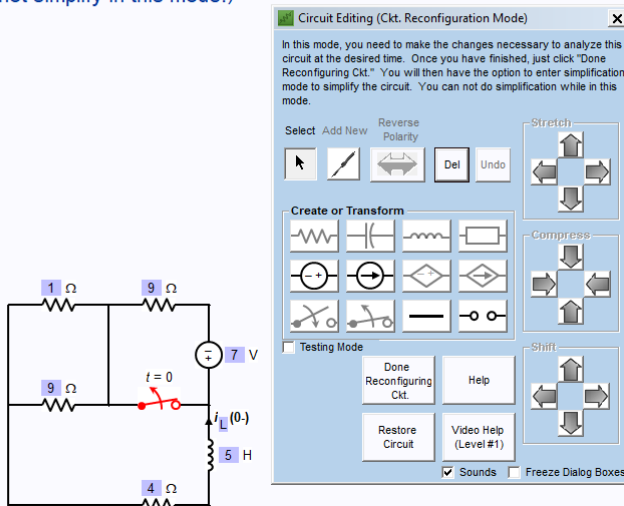9 Ω
$t = 0$
$i_L(0-)$
5 H
4 Ω

Fig. 1. Example of a first-order transient circuit being reconfigured prior to solution at $t = 0^-$.

appropriate to that time (in analogy to re-drawing the circuit on paper). At $t = 0^-$, for example, they should replace the switch by a short or open circuit as appropriate, the inductor by a short circuit or the capacitor by an open circuit due to the assumed steady-state condition, and may need to add the inductor current or capacitor voltage as a "sought variable" if they do not already exist as such so that value can be determined (see Fig. 1). They can then simplify the circuit if desired in a "simplification mode" of the circuit editor and solve for the needed variables using any method of their choice (nodal or mesh analysis, or voltage or current division if appropriate). A similar process generally applies at each other time.

At each step, students receive immediate feedback on the correctness of their editing operations, equations they have written, or values they have computed. Any errors are tracked and exceeding the limit on allowable errors of any given type results in a loss of credit for the problem (though they can still complete it for no credit, which they may wish to do if they are heavily invested in it.) They then repeat this procedure at each relevant time until all relevant parameters have been determined. Parameters they have already found are displayed on the screen for students, and every step of their work (including errors, marked as such) is recorded in the PDF "transcript" of their work (available as a record once they have completed or abandoned the problem). After finding all parameters, they are required to form the appropriate transient response equation (from building block terms that are supplied) and enter all appropriate values to check the final result.

The above process should be contrasted with the traditional one where a problem is worked on paper or in an answer-based homework system. There, a single mistake in any step of the process will result in no possibility whatsoever of a correct final answer, and students may have no idea where they went wrong. As a result, they may become extremely frustrated and unable to learn efficiently.

A similar, but more complex process is used to solve 2nd-order problems. For simplicity, the system creates only problems where the inductor and capacitor in the RLC circuit are either in series or in parallel with each other for $t > 0$, so that the remainder of the circuit can be represented as a Thévenin equivalent resistance R_{Th}. The formulas for the unknown transient $x(t)$ are more complex in this case and should be adapted depending on whether the circuit is underdamped, overdamped, or critically damped [30]. To find the second initial condition required in this case for $x'(0^+)$, students are led to solve a "first-derivative circuit" that makes this process more systematic than that used in most textbooks [30-34].

4. Laplace transform circuit analysis

Preliminary work has been performed to enable analysis of transient circuits using Laplace transforms. An example of a randomly generated circuit is shown in Fig. 2 in both the original time domain and after automatic conversion to the Laplace domain. The solution process will use the exact same procedures as in DC or AC circuits, where the object in the program that normally represents a complex number has been generalized to alternatively be a rational function of the Laplace variable **s**. The routines to add, subtract, multiply, divide, and simplify such rational functions have been created and are now being integrated into the code to enable the generation of fully worked example solutions using the existing Gaussian elimination routines. Further development will involve adapting the user interfaces to enable input of rational functions by the user in place of the real or complex numbers used now.

$$i_{1s}(t) = 7\,u(t) \qquad v_{1s}(t) = 4\cos(382\,t)\,u(t)$$

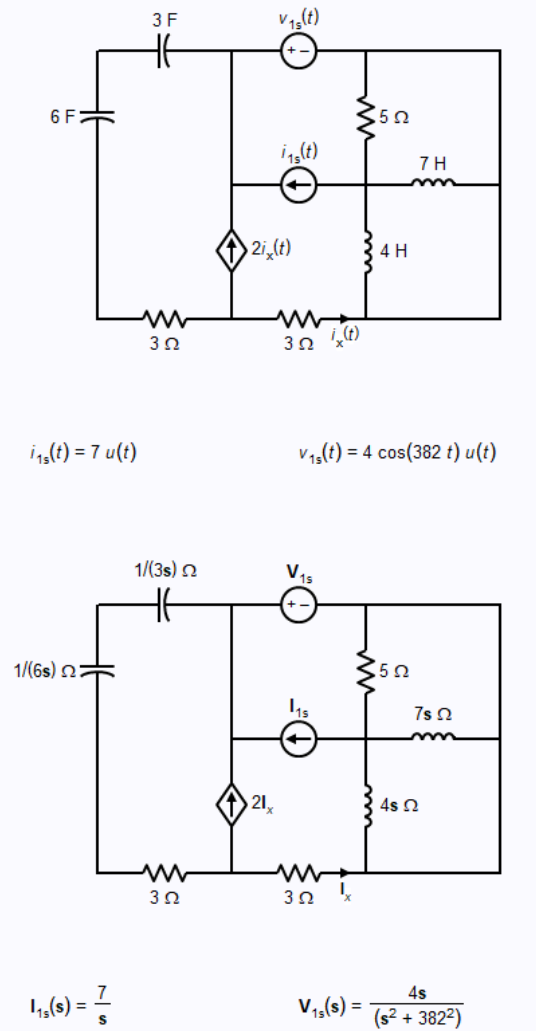$$I_{1s}(s) = \frac{7}{s} \qquad V_{1s}(s) = \frac{4s}{(s^2 + 382^2)}$$

Fig. 2. Example of a randomly generated Laplace transform circuit analysis problem in the time domain (top) and after automatic conversion to the complex frequency domain (bottom).

5. Independent evaluation results

An evaluation of the system was carried out by an independent evaluation team. The evaluation focused on implementation, usability, and satisfaction across the four participating campuses. A mixed methods approach was utilized through the combination of student and instructor surveys and document review. The survey captured both quantitative and qualitative data using Likert scale items and open-ended questions. The evaluation focused on five major questions:

1. To what extent was Circuit Tutor implemented effectively across the four partnering universities?
2. How did students perceive the utility of Circuit Tutor in supporting their course learning?
3. How did instructors perceive Circuit Tutor to impact their teaching experiences?
4. How did instructors perceive their students to experience Circuit Tutor in their course learning?
5. To what extent were students satisfied with Circuit Tutor?

The most recent evaluation focused on the Fall 2020 and Spring 2021 semesters. Across both semesters, there were 30 Circuits I courses taught, reaching 1,434 students and one Circuits II course, reaching 40 students. A total of 17 distinct instructors taught a total of 33 class sections during this time at the four institutions. A total of 21 different games (tutorials) were used. Of the total students listed within the Circuit Tutor database, 1223 were at ASU, 59 at FAMU/FSU, 91 at MSU, and 101 at UTEP.

Of this total number, faculty provided email addresses for 623 students who were then individually sent surveys. Of these 623 students at all the participating campuses in the Fall 2020 and Spring 2021 semesters, 361 students responded (58% response rate). Overall, students had very favorable experiences using Circuit Tutor across these two semesters. At least 48% of responding students in the Fall 2020 semester and 60% of students in the Spring 2021 semester agreed or strongly agreed with all these survey items on favorable aspects of Circuit Tutor (see Fig. 3).

Additional questions were added to the student survey in Spring 2021 to ask students about the utility of specific features of Circuit Tutor when learning the material (see Fig. 4). Almost half of the students (49%) agreed or strongly agreed that all aspects of Circuit Tutor were useful. The most popular features were coloring nodes and mesh currents, the ability to create as many new problems as needed to learn well and having multiple successive levels of difficulty.
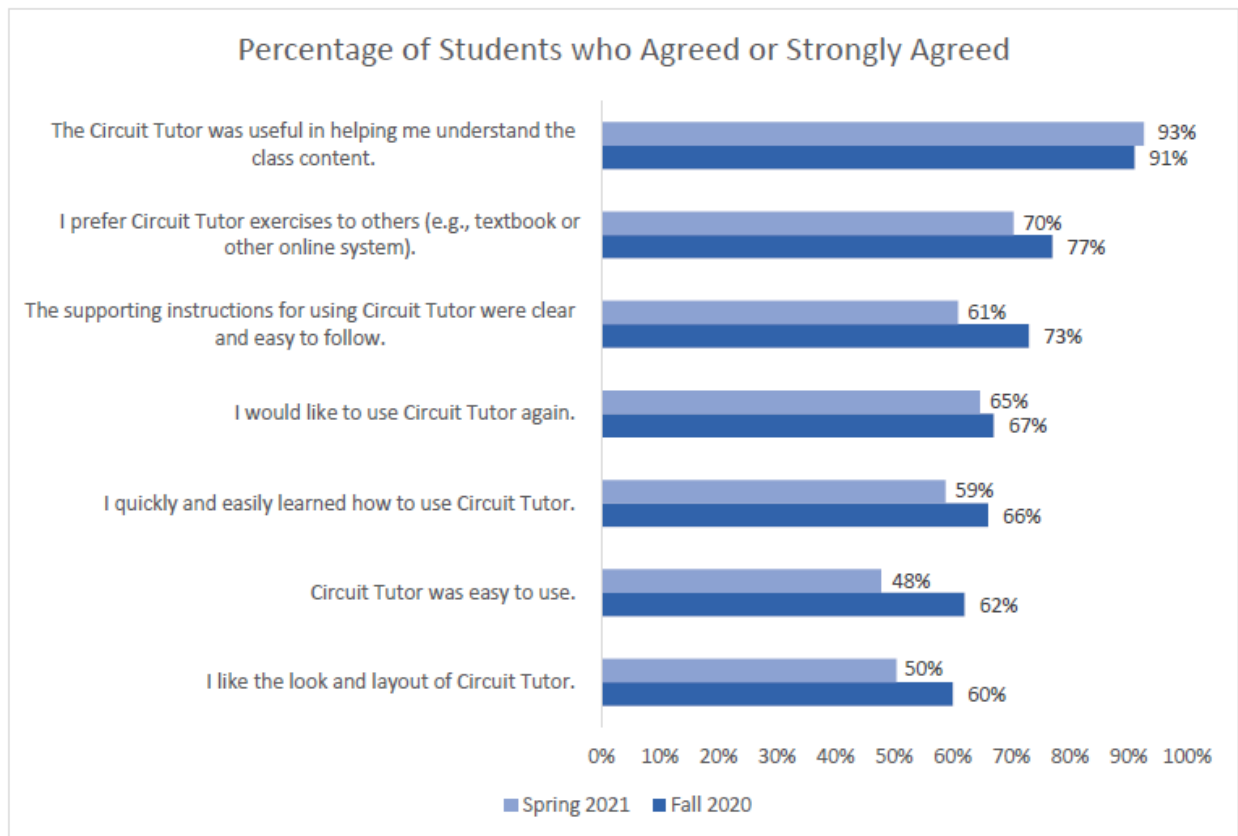

Fig. 3. Results of student survey on characteristics of Circuit Tutor in Fall 2020 and Spring 2021.
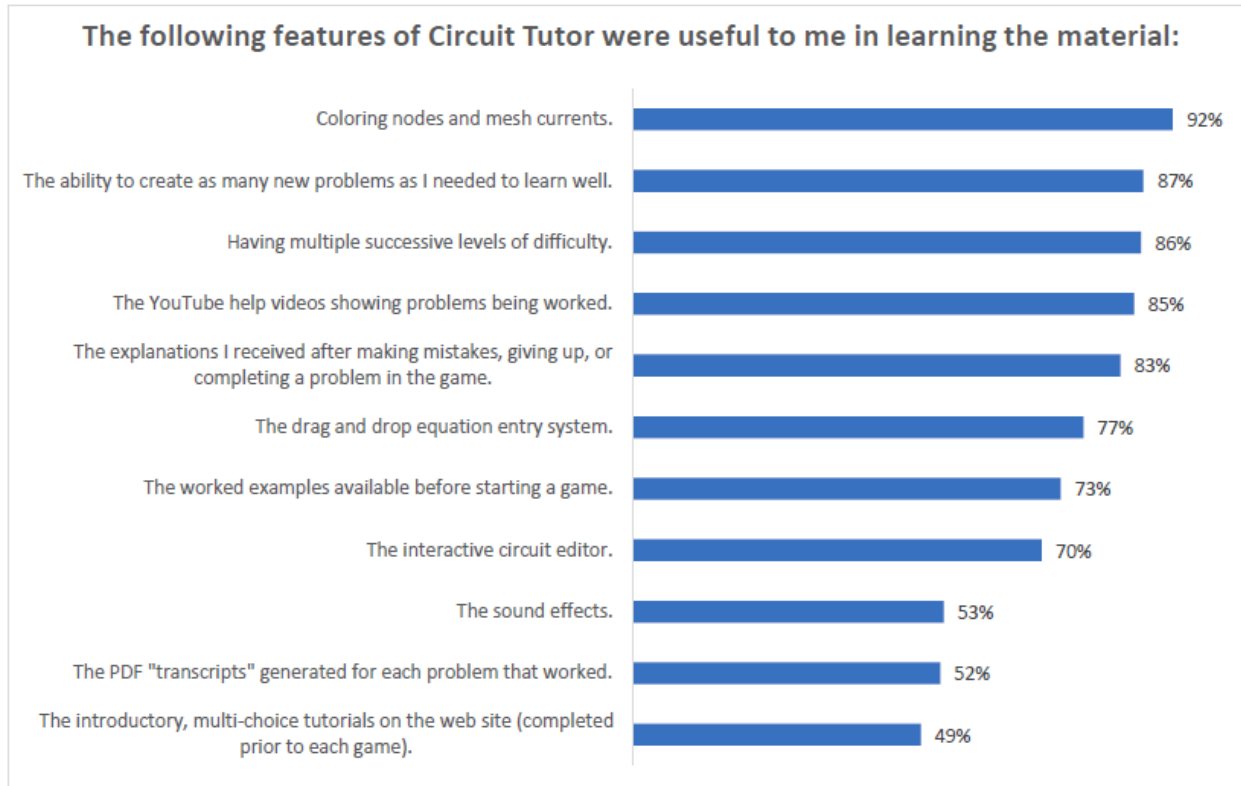
The following features of Circuit Tutor were useful to me in learning the material:

Feature	Percentage
Coloring nodes and mesh currents.	92%
The ability to create as many new problems as I needed to learn well.	87%
Having multiple successive levels of difficulty.	86%
The YouTube help videos showing problems being worked.	85%
The explanations I received after making mistakes, giving up, or completing a problem in the game.	83%
The drag and drop equation entry system.	77%
The worked examples available before starting a game.	73%
The interactive circuit editor.	70%
The sound effects.	53%
The PDF "transcripts" generated for each problem that worked.	52%
The introductory, multi-choice tutorials on the web site (completed prior to each game).	49%

Fig. 4. Results of student survey on specific features of Circuit Tutor in Spring 2021.

Instructors were surveyed in Spring 2021. Generally, they had favorable teaching experiences using Circuit Tutor. Overall, 57% (4 out of 7) of instructors reported that Circuit Tutor made teaching their classes more effective than the previously used homework system used to teach students and 57% (4/7) reported that Circuit Tutor made it somewhat or much easier to teach their classes compared to other types of homework systems for that class. Slightly less than half of the instructors (43%; 3/7) reported that their students were somewhat more motivated or much more motivated to study linear circuit analysis when using Circuit Tutor compared to the other homework system. Overall, the instructors were satisfied with their experiences using Circuit Tutor as shown through the high percentages of instructors who would recommend Circuit Tutor to other instructors (86%; 6/7); see Fig. 5. Further, 100% of the instructors reported having adequate administrative support in the program (gradebook, etc.).

Instructors were also asked about how useful several features of Circuit Tutor were to students (Fig. 6). The percentage was highest for the video (YouTube) resources and worked examples/detailed explanations (100% extremely or very useful for both), followed by the

Would you recommend that other institutions adopt CT in their linear circuit courses?
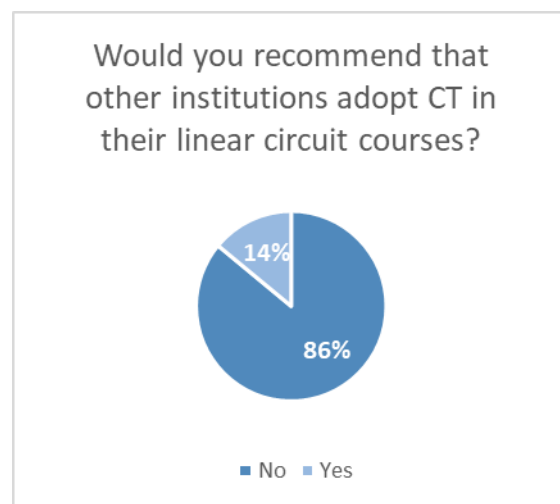
14%

86%

■ No ■ Yes

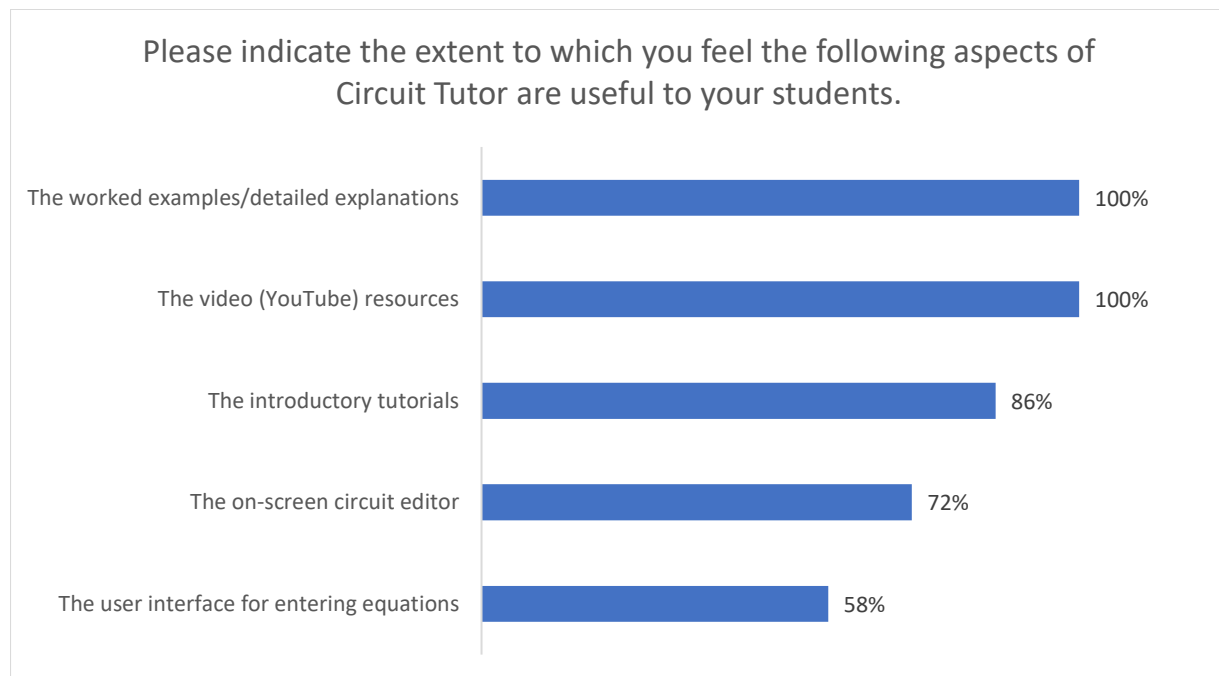Fig. 5. Results of instructor survey on characteristics of Circuit Tutor in Spring 2021.

Fig. 6. Results of instructor survey on characteristics of Circuit Tutor in Spring 2021.

introductory tutorials (86%), the on-screen circuit editor (72%), and the user interface for entering equations (58%).

To assess student satisfaction, instructors were asked some open-ended questions in their end of the course surveys in the Fall 2020 and Spring 2021 semesters. Themes that emerged for "What do you like best about Circuit Tutor?" were worked out examples/detailed explanations, practice/repetition, easy to insert and edit equations, sound effects/visualization/interactive effects, easy to insert and edit equations, and tutorial videos. Themes that emerged for "What are some of the recommendations you would make for improving Circuit Tutor?" were updating the user interface/improving the layout, increasing the number of attempts on some of the more difficult problems, and making the tutorials less wordy and more concise. Regarding the latter issues, work is in progress to transfer the code to a newer platform that would enable a more modern interface. The allowed attempts have been corrected in one or two cases where they had been set unintentionally low, and future work may include allowing students to complete a portion of a problem that caused them to fail on a different problem without having to re-work the entire problem. The issue of conciseness may be in part because students often want only the information required to work specific problems, whereas instructors may feel that general conceptual understanding is also important. However, some revisions may also be done in the interest of brevity.

Prior studies found that students preferred Circuit Tutor over the commercial WileyPLUS system for the Irwin & Nelms textbook [30] by large margins [15-19]. In Fall 2021, student surveys asked those who had used both Pearson's MasteringEngineering (for the Nilsson & Riedel textbook [32]) and Circuit Tutor which system they preferred. Over 69% of 94 students said that Circuit Tutor is much or somewhat better than MasteringEngineering, 12% felt it was much or somewhat worse, and 19% felt they were about the same. Students said they learned more, were

given more explanations, appreciated the lack of grade penalties for mistakes, had better resources such as the videos, and liked the unlimited problems and examples in Circuit Tutor. However, some preferred the simpler and easier answer-based interface in the Pearson system.

6. Conclusions

The Circuit Tutor system has been successfully extended to include problems involving first and second-order transients in switched circuits using differential equations, using a guided multi-step solution procedure. Initial work is also progressing on Laplace transform circuit analysis.

Regarding the independent evaluation, document review and surveys confirmed that all lead instructors successfully implemented the Circuit Tutor system within their classrooms. Taken together across both semesters, 92% (91% in the fall; 93% in the spring) of the students across all universities somewhat or strongly agreed that Circuit Tutor is useful in supporting their course learning and 73% agreed to the same extent that all of the features were useful in their learning. The instructor findings showed that 86% of them would recommend that other institutions use Circuit Tutor and 100% found the system provided adequate administrative support. More than half of the instructors reported that Circuit Tutor was more a more effective and easier method to teach their courses (57%) and at least 58% of them found various aspects of Circuit Tutor to be useful to their students. Overall, both students and instructors were satisfied with Circuit Tutor and they also gave constructive feedback on ways to improve it.

Students who had used both systems also preferred Circuit Tutor over Pearson's MasteringEngineering for the Nilsson-Riedel text [32] in surveys by a margin of 69% vs. 12% for the latter.

7. Acknowledgments

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