Assessment and Integration of CATE, the "Circuit Analysis Tool for Education," Into a Course Using Canvas

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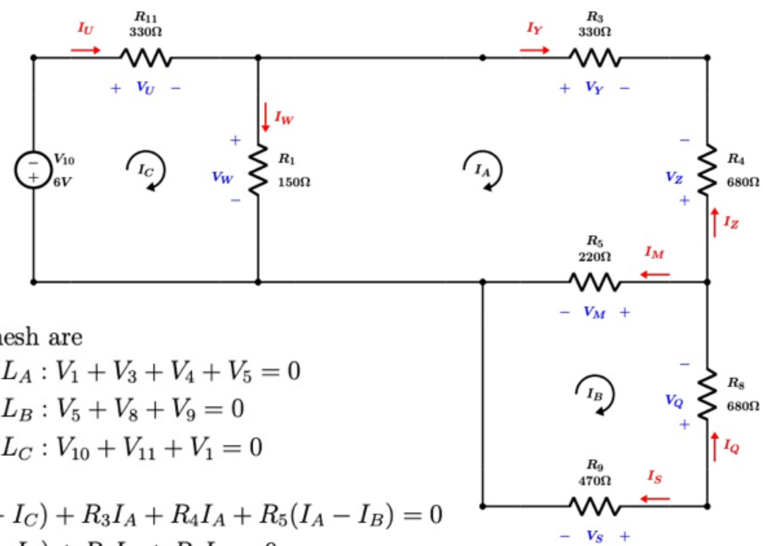
Background

The objective of this paper is to describe options for enhancing a circuit analysis course using free teaching and learning materials from CATE, the "Circuit Analysis Tool for Education." CATE is a software tool that generates circuits with randomized structure and produces step-by-step solutions with equations and detailed discussion. CATE materials have recently been formatted for Canvas [1] as a means of easy course integration. See an excerpt of a solution in Figure 1, and hundreds of examples at [2]. Via Canvas, the CATE materials can be used for examples, no-stakes practice and assessment. And, students can be assigned structurally distinct circuits for more rigorous assessment.

CATE includes topics that are typical for introductory university-level courses in circuit analysis. Topics focus primarily on linear circuits. For example, Kirchhoff's and Ohm's laws, passive sign convention, mesh and nodal analysis, superposition, Thevenin and Norton equivalents, dependent sources, op amps, transient analysis, AC steady state and AC power. Additional problems on series and parallel reductions were recently added, based on student feedback. These topics are often covered in a first or second circuit analysis course, depending on whether the class is intended for electrical engineering majors or for all engineering majors, and whether the class is offered on a semester or quarter basis. Prerequisites include possessing an introductory background from the Physics electricity and magnetism course, the ability to solve algebraic and differential equations, and the ability to perform arithmetic with complex numbers.

Solutions generated by CATE include an overview describing the what, why, and how, of a given analysis technique. The foundational principles of a technique—Kirchhoff's Voltage Law (KVL) for mesh analysis and Kirchhoff's Current Law (KCL) for nodal analysis, for example—are then described for the general case, followed by step-by-step details with specific equations for the given circuit. See Figure 1. Numerical values for currents and voltages are validated using NGspice [3]. A final schematic is annotated with voltages and currents for each element, and a table describes the power absorbed by each element. This summary information intended to promote learning by scaffolding [4] by fostering connections between underlying concepts that are relevant to the analysis.

The CATE software was recently upgraded to improve graphics and to expand the discussion presented in the step-by-step solutions. Formatting for Canvas as Course Export Modules was also recently completed. These upgrades provide examples, no-stakes practice problems and question banks for assessment in Canvas.



Hence, the KVL equations for each mesh are

$$\begin{cases} KVL_A : V_1 + V_3 + V_4 + V_5 = 0 \\ KVL_B : V_5 + V_8 + V_9 = 0 \\ KVL_C : V_{10} + V_{11} + V_1 = 0 \end{cases}$$

$$\begin{cases} KVL_A : R_1(I_A - I_C) + R_3 I_A + R_4 I_A + R_5(I_A - I_B) = 0 \\ KVL_B : R_5(I_B - I_A) + R_8 I_B + R_9 I_B = 0 \\ KVL_C : V_{10} + R_{11} I_C + R_1(I_C - I_A) = 0 \end{cases}$$

Introducing coefficients based on component values

$$\begin{cases} KVL_A : 150(I_A - I_C) + 330 I_A + 680 I_A + 220(I_A - I_B) = 0 \\ KVL_B : 220(I_B - I_A) + 680 I_B + 470 I_B = 0 \\ KVL_C : 6 + 330 I_C + 150(I_C - I_A) = 0 \end{cases}$$

Expressing in matrix form

$$\begin{bmatrix} 1380.0 & -220.0 & -150.0 \\ -220.0 & 1370.0 & 0.0 \\ -150.0 & 0.0 & 480.0 \end{bmatrix} \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} = \begin{bmatrix} 0.0 \\ 0.0 \\ -6.0 \end{bmatrix}$$

Solving the matrix equation yields the following numeric values

$$\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} = \begin{bmatrix} -1.445\,\mathrm{mA} \\ -232.0\,\mathrm{uA} \\ -12.95\,\mathrm{mA} \end{bmatrix}$$

Figure 1: Excerpt of a step-by-step solution for mesh analysis generated automatically by CATE. The complete example also includes questions and answers on specific voltages and currents (*e.g.* I_Q and V_Q), and a discussion of the principles of the analysis technique. Circuits are randomly generated, subject to constraints on problem difficulty.

Research questions

Prior published results [5] suggested that students can perform better on traditional in-class exams if they practice with CATE. The objective of this current study is to gauge the overall value of CATE materials relative to other resources, and to determine what topics may require expansion, following the recent upgrades. The following research questions are posed.

1. How do students perceive the value of CATE versus other resources?
2. Is the current scope of CATE materials sufficient in students' view?

Benefits of incorporating many circuits with randomized structure into a course

Randomized aspects of a circuit include the location and type of sources, their polarity, the number of sources, the arrangement of meshes, and component types and values. The questions posed to students also vary randomly. For example, with a mesh analysis, questions on voltages for passive elements include some cases that require negation of the mesh current and other cases that do not, based on the defined voltage polarity. As another example, questions on voltages include cases for elements on unshared branches (requiring a single mesh current), as well as elements on shared branches (requiring two mesh currents).

Note that randomized circuit generation is performed in a controlled manner to yield sets of circuit problems that require similar levels of difficulty for students. For mesh and nodal analysis, a useful measure of difficulty is the number of simultaneous equations. With this metric, difficulty can vary depending on the number of sources, meshes, nodes, as well as source locations and source types.

Incorporating many randomized circuits into a course can provide several benefits. For example, it can expose students to conditions or variations that they may not have considered and thus help them discover shortfalls in their abilities. It might also catch the attention of an overconfident student who mistakenly assumes expertise [6]. Also, reviewing large numbers of varied problems has been shown by Brown [7] to help students retain their abilities longer. Large sets of problems can also be used for no-stakes practice, permitting students to validate their abilities and potentially improve confidence without substantially increasing instructor workload. And, as Lang [8] describes, student organizations often pride themselves on having stockpiles of old exams and homework. Thus, refreshing problems on a regular basis makes it more difficult for students to cheat by copying old homework solutions.

Using the Canvas quizzing engine and the CATE materials, options for assessment include assigning distinct circuits to each student, assigning common circuits, or a mix or both. The intent of the distinct circuits is to provide an environment where students can work together while each must still analyze their own circuit. More specifically, students cannot simply copy an analysis from others because the structurally distinct problems require the derivation of different equations for each circuit. A case can be also made for assigning some circuits that are identical. While these assessment problems can be copied directly by students who cheat, the common problems may also provide some benefits to more scrupulous peer learners. For example, common problems have a lower barrier to collaboration. They also allow peers to more readily explain an analysis to another student. The appropriate mix of common and distinct problems may depend on whether the course design goal is to optimize assessment or to optimize peer learning [9].

In addition, no-stakes practice problems that are presented in a test-like environment have been shown to improve student recall due to the testing effect [8]. Practice problems can also provide guidance to students in a peer learning environment [10]. This can help mitigate concerns with (inadvertent) faulty guidance from fellow students.

Comparison with other systems

A brief comparison is included here, as prior publications [5] have included a more extensive review of other systems. The key benefits of the updated CATE materials derive from the large number of structurally distinct circuit problems, with detailed solutions, and the integration with Canvas.

Compared to SPICE, CATE provides intermediate equations as part of the generated solutions. Thus, CATE helps develop a student's formative abilities, versus simply checking their summative performance. Also, SPICE programs also do not automatically generate circuits that are appropriate to a given learning objective or difficulty level. The autocircuits.org system [11] does generate random circuits but (as with SPICE) only presents the final numerical results, not the intermediate steps of an analysis. This helps verify abilities but is not developmental in nature.

The native quizzing engines in Moodle [12] and Canvas [1] allow instructors to introduce a randomized parameter for individual questions, thus providing different numerical answers. However, the equations derived by a student in these problems would essentially be identical, except for the random parameter value. Hence, these systems permit key steps to be copied from student to student. This environment is more susceptible to cheating and does not promote deep engagement for peer learners.

Close neighbors to CATE include systems such as ZyBooks [13], Mastering [14], and Wiley+ [15]. These systems typically have direct links to, or are embedded within, textbooks. As such, the linked textbooks provide examples and hints. These systems also typically include their own assessment engines. In contrast, the CATE/Canvas materials are designed for easy and flexible integration into an existing course with minimal changes to the class. Also, the CATE materials permit structurally distinct circuits to be assigned to students for assessment. This helps mitigate cheating [8]. And, quizzes can be setup in Canvas that permit retries with new circuits. This similar to a competency-based environment [16] (albeit with a limited number of retries).

A nearest neighbor to CATE is the system developed by Skromme [17, 18] which also generates random topologies, with detailed solutions. Skromme's efforts are geared towards tutoring, whereas CATE provides examples, practice and assessment materials. In addition, CATE materials can be imported into Canvas to facilitate course integration.

Options for integrating CATE materials into a course

Several options for integrating CATE materials are presented next. Suggestions for using the CATE/Canvas environment in educational research is also described.

Include the CATE website URL on a syllabus

A simple one-minute approach is to include `YourLearningCoach.org` as an additional reference on the course syllabus. Students can then peruse materials and download examples with detailed solutions, based on their interest. This scenario is a simple approach and may not engage students as well as if the materials are imported into Canvas and coordinated with course content. This method also does not provide a means to monitor students' usage of the CATE materials for purposes of educational research.

Use CATE materials in Canvas for practice

Table 1: Practice problems are defined as no-stakes quizzes in Canvas and include multiple questions per circuit (e2025-v1.2 edition). Solutions are available. The practice problems shown here provide an example of the ones available for mesh analysis.

Number of circuits	Total number of questions	Subtopic/Learning objective for mesh analysis
4	20	with Voltage Sources and 2 Meshes
4	36	with Voltage Sources and 3 Meshes
4	24	with Isolated Current Sources
4	24	with Current Source on a Shared Branch

All the circuits associated with practice problems for a given topic (e.g., mesh analysis) appear on a single page in Canvas. These include circuits associated with each learning objective under a topic (see Table 1). For example, for mesh analysis, the circuits include cases with only voltage sources, with current sources on isolated branches, and with current sources on shared branches. Each of these cases require variations on the mesh analysis technique but are presented side-by-side on the Canvas page. Thus, the collection of examples under a given topic not only include varied structures but also include nuanced differences in analysis techniques. The goal of this presentation is to encourage students to appreciate the subtleties introduced by these variations, rather than simply tell students which specific approach is needed for a given circuit. Practice problems include multiple questions per circuit. By default, students have unlimited attempts on these practice quizzes and solutions are available after the first attempt.

Use CATE materials in Canvas as examples

This option is similar to the above case involving practice materials. However, with the example problems, the solutions are provided directly to students via a link without any practice questions.

Table 2: Assessment problems are defined in Canvas question banks with one question per circuit (e2025-v1.2 edition). Instructors can define quizzes that draw from the question banks and can set quiz parameters (e.g. number of attempts) as desired. These assessment problems shown here illustrate the ones available for mesh analysis only.

Number of circuits	Total number of questions	Subtopic/Learning objective for mesh analysis
34	34	with Voltage Sources and 2 Meshes
34	34	with Voltage Sources and 3 Meshes
30	30	with Isolated Current Sources
30	30	with Current Source on a Shared Branch

Use CATE materials in Canvas for assessment with distinct circuits

Question banks generated by CATE can be loaded into Canvas via Course Export Files. Table 2 describes the question banks associated with mesh analysis, as an example. Instructors can define quizzes as desired - setting the number of retries and other options [19].

One approach here is to define a quiz with several retries, a single circuit, and a single question on that circuit. After submitting a response to a quiz problem, students can review the solution via the feedback mechanism within Canvas. If the student requests a retry, then a new circuit is randomly selected from the question bank. In this approach, students only repeat the analyses that they get wrong. And they can see the solutions following an incorrect response. This gives the student an opportunity to learn from their mistakes (via the solutions) and then try again.

If students are given several retries, then this approach approximates competency-based grading [16, 20] by providing multiple opportunities to demonstrate proficiency. For a more challenging and more traditional approach to assessment, instructors can define quizzes without any retries.

Use CATE materials in Canvas for assessment with common circuits

Another option is to use CATE question banks to setup quizzes that use circuits which are common for all students. This is rather like traditional homework, except that the problems can be easily refreshed each year.

Comparing different options

Table 3 summarizes different options for including CATE materials into a course. These options are not mutually exclusive. Including the CATE website URL on a syllabus is not included in the table below.

Limitations related to the Canvas quizzing engine

The above options are constrained by an unfortunate limitation of the Canvas quizzing engine. Canvas can assign a single circuit problem with multiple parts (A-G) to each student. It can also assign a single circuit problem with a single question to each student, using a question bank.

Table 3: Comparison of options for integrating CATE materials into a course via Canvas.

Approach	Purpose	Usage
Examples	Developmental	Students peruse circuits and download examples
Practice	Developmental	Peruse circuits and must attempt one problem before accessing solutions
Homework	Assessment	Common circuits for each student, several questions per circuit
Quiz	Assessment	Distinct circuits for each student, one question per circuit

Unfortunately, Canvas cannot assign distinct multipart questions to each student. For example, assigning questions 1A-1G on circuit 1 to student 1, assigning 2A-2G on circuit 2 to student 2... is not possible. Thus, students cannot each be assigned a distinct circuit problem with multiple questions on that circuit. In practice, students have voiced displeasure at the limitation associated with assessment problems.

Tools for educational research using CATE materials in Canvas

Prior published results on CATE [5] suggested that students can perform better on traditional in-class exams, if they practice with CATE. This study used a regression analysis to predict exam scores, with GPA and CATE usage (clicks) as dependent variables. As such, this study was a quasi-experiment because students opted in to using CATE.

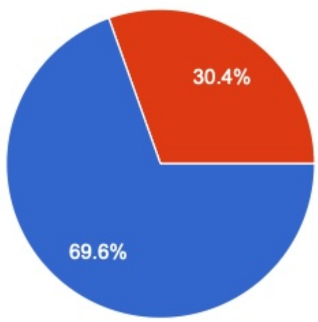
The raw data needed to repeat this prior study can be collected and stored securely within Canvas. For example, GPA can be collected using a survey (with appropriate IRB approval and student's consent). The usage of CATE practice problems can be acquired by accessing the "Moderate this Quiz" page on Canvas and then copying and pasting the table shown into a spreadsheet. And, exam scores can be recorded in the grade book. This approach permits all the raw data associated with the prior study to be consolidated within Canvas.

Evaluation of research question 1: How do students perceive the value of CATE versus other resources?

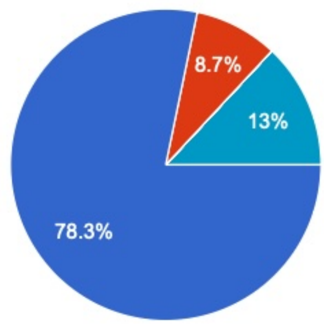
A survey was used to query students regarding their perceived value of various learning resources. Students responded using a Likert scale: Always, Very Often, Sometimes, Rarely, Never and Not Applicable. Table 3 gives the percentage of Always or Very Often responses, sorted highest to lowest. A total of 23 students completed this survey. Figure 2 shows the percentages for each Likert response.

Using CATE and asking the instructor were ranked highest by the students. The perceived benefit of CATE was also ranked higher than tutoring, Google searches, and the textbook.

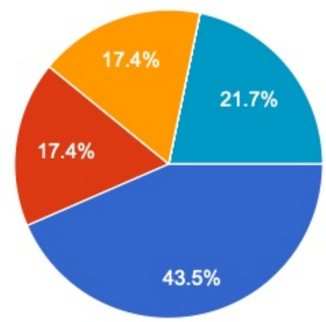
[1] The other 13% responded "Not Applicable."



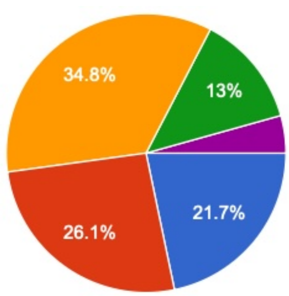
(a) "Reviewing CATE practice problems was helpful."



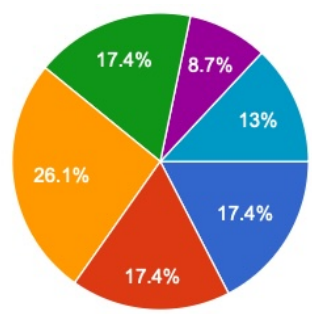
(b) "Asking the instructor questions was helpful."



(c) "Tutoring center resources were helpful."



(d) "Google searches were helpful."



(e) "Reading the textbook was helpful."

Figure 2: Survey responses ($N = 23$) examining the perceived value of various learning resources. Using CATE and asking the instructor were ranked highest by the students.

Table 4: Sorted summary of responses with students ranking the helpfulness of various resources. Percentages indicate the sum of "Always" and "Very Often" out of $N = 23$ responses.

Question prompt	Response fraction [%]
"Reviewing CATE practice problems was helpful"	100
"Asking the instructor questions was helpful"	87[1]
"Tutoring center resources were helpful"	61
"Google searches were helpful"	46
"Reading the textbook was helpful"	35

Evaluation of research question 2: Is the current scope of CATE materials sufficient in students' view?

Regarding the potential expansion of topics for the CATE materials, students responded with the preferences shown in Table 5. Responses (N=20) are sorted, showing the percentage responding with Always or Very Often. Figure 3 provides more detail on the Likert responses.

Table 5: Summary of responses with students ranking the helpfulness of various resources. N=20. Generally, students seemed comfortable with the topics provided within CATE. Their interest was primarily in seeing more advanced topics.

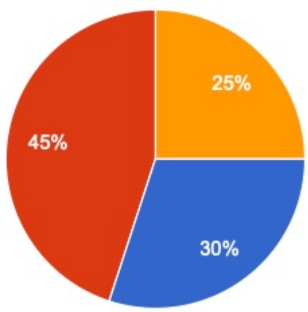
Question prompt	Response fraction [%]
"Introduce more advanced content (e.g., diodes, transistors, Fourier and Laplace transforms)"	75
"Include case studies or applications as examples"	70
"Add more content related to manipulating complex numbers"	65
"Add more content related to prerequisites from physics, such as how capacitors and inductors work from an E&M perspective"	60
"Add more content related to solving differential equations"	45

It was surprising that the top preference for expanded content was to include more advanced topics. Also surprising was the lowest ranking for differential equations. This may be because most students have just completed a course on this topic, or are taking it concurrently.

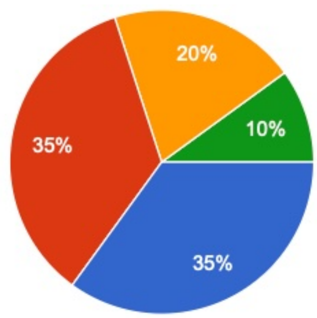
Dissemination plan

CATE topics were established to align closely with a shared syllabus used across the California community college system. This systemwide syllabus was established via a faculty-led effort to support course articulation and to facilitate student transfer [21]. At present approximately 60% of the 116 California community college institutions teach circuit analysis. Hence, the topics available in CATE can potentially support many students. CATE topics may also be useful when reviewing for the general part of the Fundamentals in Engineering exam [22].

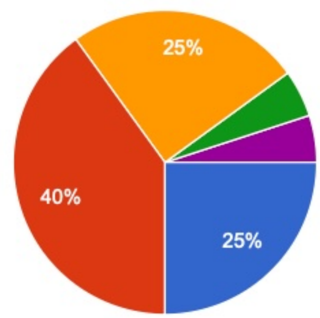
CATE/Canvas materials can also benefit institutions that use no-cost textbooks available through OER Commons [23] and Educause [24]. These no-cost resources typically lack companion web-based assessment systems provided by publishers of higher cost textbooks. Thus,



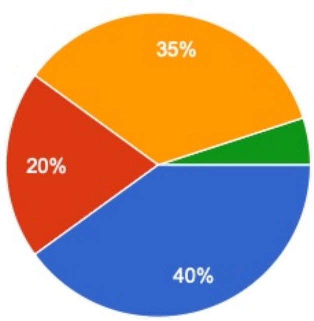
(a) "Introduce more advanced content."



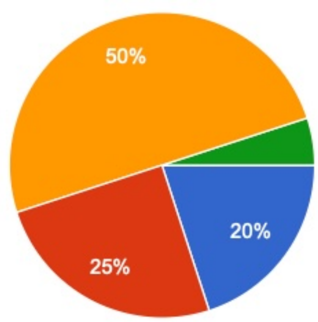
(b) "Include case studies or applications."



(c) "Add more on complex numbers."



(d) "Add more from physics prerequisite."



(e) "Add more on solving differential equations."

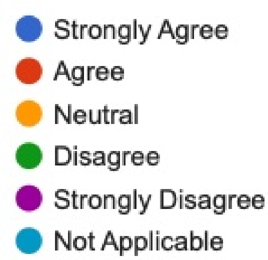


Figure 3: Likert responses for survey question on sufficiency of content in CATE. N=20.

CATE/Canvas materials provide a no-cost alternative for assessment and practice that may enhance open educational resources.

CATE materials are licensed under a Creative Commons Attribution 4.0 International agreement [25]. As such, these materials are free with unrestricted usage, provided an attribution is included. The license agreement extends to derivative works for commercial purposes.

Summary and conclusion

The goal of this paper is to promote dissemination of the CATE materials. Recent improvements allow these materials to be imported directly into Canvas. This facilitates integration of the materials into a course. Assessment of students' perceptions suggest that the CATE materials rank well relative to other materials, and that further extensions could target advanced topics.

Planned near-term upgrades will address accessibility to improve conformity with the US Department of Justice ADA requirements [26]. Typesetting for the solutions is accomplished using LaTeX [27], which has libraries available to improve accessibility of content. The current plan is to employ these libraries when generating the solution file PDFs. Other development tasks are ongoing, including the creation of sets of workbooks designed to facilitate peer learning. Each workbook in the set would have structurally distinct circuits for assessment.

Instructors can email `contact@YourLearningCoach.org` for information on how to access the Canvas Course Export Files. Requests for additional topics, new styles of questions, and encouraging suggestions for improvement are welcome.

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