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Improved Student Learning in a Circuits Course with a Novel Web-Based System

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Introduction

A multiyear (unfunded) development effort has led to the creation of a web-based teaching and learning system for circuit analysis. A key feature of the "Circuit Analysis Tool for Education" (CATE) system is the ability to automatically generate topologically distinct circuits with step-by-step solutions. These problems are used for examples, practice, and for out-of-class assignments. Circuit problems can be readily refreshed for each new section of a course. The course associated with this study was one for non-majors and covers DC analysis, AC phasors and AC power, as well as transient analysis. This paper examines the improvement to student exam scores on traditional in-class midterms. Results show the strong dependence of exam scores on cumulative GPA, but also demonstrate that lower-GPA students can break away from this trend by using the CATE system. The authors feel that it is an important metric for a teaching and learning system, as it promotes success for a wide range of students.

The CATE system is a 24/7 resource providing examples, practice and assessment. Students were encouraged to work together on out-of-class quizzes, and to use CATE to guide their peer learning via examples and practice. Topologically distinct circuit problems were assigned for out-of-class assessment, to mitigate concerns with cheating. The intention here was to create an environment where students can work together but cannot simply copy answers, thanks to their own distinct circuit. The CATE system is well suited for peer learning, but performance of independent learners is of interest as well; both groups are described in the results.

This study involved quantitative data. Student usage of the CATE system was captured by logging mouse clicks. Students' cumulative GPA was imported from campus archives. Surveys helped determine students' preferences for either independent or peer learning, as well as their choice of learning resources. Students were not required to use CATE. Hence, the study involved quasi-experimental conditions. The class associated with this study had 34 students, nearly all of whom chose to participate, including both independent and peer learners.

An additional motivation for this study was to inform software development efforts associated with a major revision to CATE. In this regard, the study should have been completed sooner! Next steps and future directions for the CATE system are discussed.

This paper has 3 major parts: 1) The approach used for peer learning, 2) Why systems such as CATE are needed, and 3) Statistical analysis of the benefits of CATE on student learning.

What functionality makes CATE unique?

At the heart of CATE is an expert system that generates random circuit problems with detailed solutions. Uniqueness is due to a combination of four capabilities:

1. Randomized circuit generation with millions of topologies. See Figure 1. Circuit generation is constrained to create sets of quiz problems with similar difficulty.
2. Detailed solutions with step-by-step equations, specific to a given circuit, are automatically generated. These equations mimic a student's analysis effort. See Figure 2.
3. Nearly unlimited no-stakes practice problems are available to students.
4. Assigned quiz problems are distinct for each student. Problems are automatically graded and detailed solutions are provided. Instructors can also monitor quiz progress before assignments are due.

Generating circuits with random topologies and random component values is considered a key technical advantage for CATE [1][2]. First, this circuit-generation capability broadens a student's exposure to a range of analysis conditions (items 1 & 2 above). This complements lecture material by demonstrating different ways that concepts combine in analysis problems. Secondly, generating distinct circuit problems provides numerous opportunities for practice and assessment (items 3 & 4 above). Circuits are created by randomly combining rectangular shapes, which establish the meshes of a circuit. See Figure 1. An example of an automatically generated circuit and associated solutions are shown in Figure 2. This example is from the revised version of CATE, which is under development as of the date of this publication. The original version is available currently at YourLearningCoach.com.

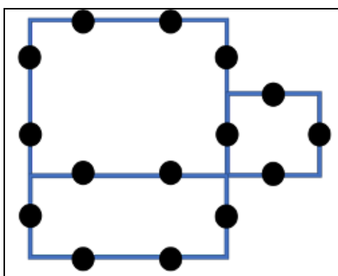
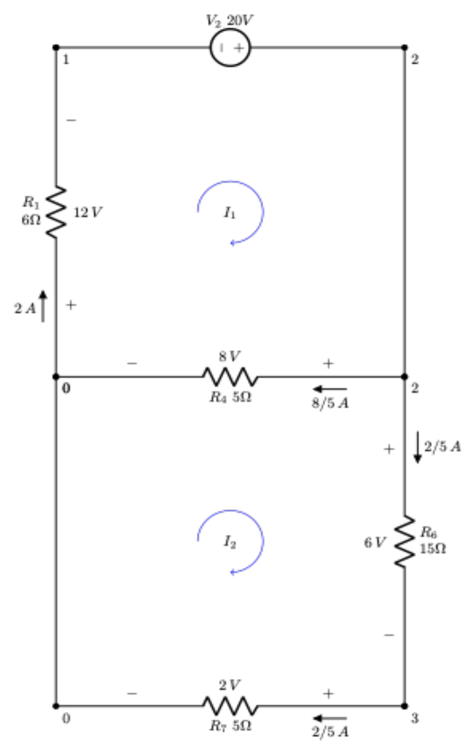


Figure 1. A three-mesh circuit topology formed by randomly placed rectangles. Each of the 15 dots represents a location that a resistor, inductor, capacitor, source, or wire could be instantiated. This topology can form the basis for over 4^{15} ($\sim 10^{9}$) different circuits and is just one arrangement of meshes that can be randomly generated with a few rectangular building blocks.

How CATE enables a peer learning environment.
In the course associated with this study, students were encouraged to work together and to use CATE to supplement their peer learning efforts. Boud [3] describes peer learning as "students learning from and with each other in both formal and informal ways". The informal aspect of peer learning refers to an incidental and often reciprocal style, without a tutor or instructor [4]. Informal peer learning differs from collaborative or cooperative learning [3][4][5] as these styles are typically more structured and require more instructor involvement.

According to Boud [3] students in a peer environment often communicate more, articulate understanding and are more open to criticism, compared to when faculty or staff are present. Peer learning can also help students develop lifelong learning abilities, in addition to critical inquiry, reflection, teamwork, and communication skills [3]. And finally, from [6] "We know from research that the more students engage with other students in the class, as well as with professors, the more likely they are going to stay and get their baccalaureate degrees." Boud [3] also suggests that peer learning suits some students better than learning individually, particularly women and students from some cultural backgrounds.

The approach here is to use CATE to enhance learning in a peer-learning environment. This is intended to provide the many benefits of peer learning without an increased time commitment for the instructor.



To use mesh analysis, first identify the number of meshes. In this case there are 2, which is also the number of equations. Choose a CW direction and label the unknown mesh currents: I_1, I_2.

Observe passive sign convention and apply KVL, choosing the CW direction. Describe each voltage in IR form, using the mesh currents

$$\begin{cases} I_1 : (R_1)I_1 - (V_2) + (R_4)(I_1 - I_2) = 0 \\ I_2 : (R_4)(I_2 - I_1) + (R_6)I_2 + (R_7)I_2 = 0 \end{cases}$$

Introduce component values

$$\begin{cases} I_1 : 6I_1 - 20 + 5(I_1 - I_2) = 0 \\ I_2 : 5(I_2 - I_1) + 15I_2 + 5I_2 = 0 \end{cases}$$

In matrix form this is

$$\begin{bmatrix} 11.0 & -5.0 \\ -5.0 & 25.0 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} 20.0 \\ 0 \end{bmatrix}$$

Which yields the following mesh currents

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} 2 \\ 2/5 \end{bmatrix} = \begin{bmatrix} 2.0\,\mathrm{A} \\ 400.0\,\mathrm{mA} \end{bmatrix}$$

Figure 2. A randomly generated circuit and associated step-by-step analysis. The CATE system includes an algorithm to select component values that yield "nice" values for currents. Circuit and solutions are automatically generated.

Research questions examine the effectiveness of CATE.

The purpose of this study is twofold: first, to demonstrate the benefits of CATE on student learning, and second, to gain critical insight regarding needed improvement areas for the CATE system. Student performance was measured using midterm scores on two traditional in-class exams. The following research questions were examined for both peer learners and independent learners.

- How often are various features of the CATE system being used?
- Will students perceive a benefit from it (both independent and peer learners)?
- Can CATE provide an effective learning resource, and improve student performance on traditional types of assessments (for both independent and peer learners)?
- Can instructors use CATE in a manner that benefits student learning, while minimally impacting their own teaching approach?

The importance of supporting students with different academic journeys!
It is common for students to have varying degrees of preparation for a course based on their respective life experiences and academic journeys. These variations can occur for many reasons, some more visible than others. For example, transfers from community colleges, transfers from international universities, or students who change majors [7][8][9] have not had the same in-major preparation as students who start as freshman at a given university. In other cases, the reasons may not be as readily apparent. For example, students who are first-generation, students who lack inclusion and feel isolated, non-traditional students including those with family commitments, as well as veterans [10] and students struggling with mental health challenges.

Part-time students are another group with varying preparations, perhaps because of larger gaps between prerequisite courses. Part-time status may be due to financial hardship, illness, or family commitments, for example. Many studies report increasing numbers of students who are part-time [11]. This suggests that the need for scalable approaches to support students, such as CATE, may be increasing.

In some cases, students with different academic journeys may have different styles of preparation. And in some cases they may also have lower GPAs than students who have not faced challenges of changing institutions, or majors, or part-time enrollment, for example. The authors' perspective is that a lack of prerequisite knowledge or a lower GPA does not necessarily suggest a lower potential. Furthermore, the authors feel, a well-designed course should include appropriate resources to support all students. It is worth noting that additional resources can benefit students beyond a target audience, as suggested in studies on Universal Design for Learning [12][13]. Thus, additional resources for some can ultimately help many more.

A goal for the CATE system is to provide an environment in which all students can succeed, regardless of varying academic journeys.

CATE builds on established best practices.
The CATE system has many features that are consistent with many best practices for teaching and learning. For example, Lang [14] examines many issues behind students' motivation for cheating and ways to redesign a course to mitigate dishonesty and to encourage deeper learning. Lang describes using "grounded assessment" to help reduce cheating. This process involves establishing new assessments that are unique to each course and each semester. Lang also notes that many student organizations pride themselves on retaining exams and homework from prior semesters and make these available to their members. He also argues that environments that reduce the opportunity to cheat also encourage greater and deeper learning. As described, generating distinct circuit problems is a key feature of the CATE system.

In [15], Young suggests that having "numerous opportunities to practice … will enhance intrinsic motivation by developing student competencies." Cross disciplinary studies [16][17] have shown that long term retention was improved when students were presented with cases that were similar but not identical to a desired example. This is also referred to as the "Make It Stick" approach. The "testing effect" [14][16] suggests similar benefits to improve retention. The no-stakes practice problems in CATE are consistent with the recommendations of these many studies.

How does the CATE learning environment compare to other systems?
There has been a surge of online teaching and learning systems in recent years. For comparison purposes, other systems are grouped into functional categories A-D.

A. Circuit analysis systems.
Many variants of SPICE are available at no cost and are powerful analysis tools [18][19]. However, these do not have features that are needed for teaching and learning systems. For example, they only provide final numeric results. They do not describe intermediate equations. Also, these tools do not provide features for assessment (e.g., problem assignment, question and answer generation, automatic grading). The Autocircuits.org system is a step up from SPICE. It does automatically generate circuits and provides final numeric results. However, it does not provide any explanation of the analysis steps. As with SPICE, it can be used to verify students' abilities, but not for teaching analysis or for tutoring purposes.

B. Learning systems integrated with textbook-style resources.
This category of learning tools has seen rapid growth and adoption in the past decade. From a teaching and learning perspective these tools are among the most powerful. For example, Mastering by McGraw Hill [20], Wiley Plus [21], and ZyBooks [22]. These tools typically have links into textbook materials or are embedded within textbook resources. Some of these systems include related studies reporting improved grades [23]. However, available systems do not provide detailed step-by-step solutions that are specific to a given problem. They also lack the ability to generate circuits with random topologies and component values, which is a key advantage of CATE to mitigate concerns with cheating and promote a strong peer learning environment.

C. Quizzing engines within learning management systems.
Learning management systems such as Canvas [24] and Moodle [25] typically include quizzing engines. The WebAssign [26] system is also included in this group. It includes a quizzing engine and can integrate with learning management systems. WebAssign provides considerable flexibility to create questions and other content.

A common question type for these kinds of systems involves questions that incorporate randomized parameters. Instructors establish the correct answer to a problem by defining a formula that is based on the random value. This provides a convenient mechanism to create distinct problems. However, (in the context of circuit analysis problems), this permits variations in component values to be introduced; it does not provide randomized circuit topologies. To introduce many different circuit topologies, an instructor would need to establish a bank of questions covering the desired range of circuit conditions. In contrast, CATE has the circuit generation capability integrated with the teaching and learning tool. And CATE can generate millions of circuit topologies.

D. Collaboration-Only tools
Many online collaboration tools are available for academic question-and-answer sessions. Some are integrated with learning management systems (e.g., Canvas [24], Moodle [25]). And some are standalone, such as Piazza [27] and Discord [28]. These tools can be used in a

moderated or unmoderated fashion in a classroom setting. Messaging from an instructor can reach every student. These collaboration tools do not include any discipline-specific features (e.g., circuit analysis). However, users could post links to circuit examples as part of the Q&A discussion.

Compared to the above categories of systems, the key novelty of CATE is the ability to generate random circuit topologies and present an analysis in a step-by-step manner. Outside of the above categories, one nearest neighbor is known to exist (as of this publication). A system developed by Skromme [29] [30] also generates random topologies, with detailed solutions. Skromme's efforts are geared towards tutoring, whereas CATE focuses on providing examples, practice and an integrated quizzing engine. A system by Hayes [31] also deserves mentioning. It provides solution details for a circuit analysis. However, it does not generate random circuits and does not include tutoring, automatically generated examples, practice problems or assessment.

Results indicate that students who used CATE can perform better!

The effort to formally evaluate the effectiveness of CATE required many trial runs prior to this publication. The process included many eye-opening surprises. For example, early results were, at first, disconcerting when a negative correlation was found between CATE usage and exam grades for the high achieving students. It was soon realized that the top GPA students are likely to be less challenged by the class; hence they don't need the assistance of a system such as CATE. Following this realization, attention turned quickly to examine the impact of CATE on students with lower GPAs. More broadly, this observation led to the realization that student GPAs should be included in the statistical analysis.

An early attempt at using student GPA involved splitting students into tiers (e.g., under 2.5 GPA…) and looking for significant differences in exam scores between groups. Some experiments yielded interesting results; however, this approach was set aside because the basis for groupings was arbitrary in nature. Also note that a prerequisite for t-tests is a normal distribution, which is lacking for much of this data. The first set of results below employed a regression analysis using student GPA variables and CATE usage data. (This approach avoided arbitrary thresholds on GPA.)

Another area of consideration was the means to quantify usage of CATE. Various types of usage data had been logged for each student, and a question remained regarding which to use or how to combine them. Logged data was associated with different kinds of mouse clicks within CATE. For example, clicks on practice problems, on no-stakes examples, and on quiz access. Numerous options were checked experimentally. Ultimately, usage was defined as the sum of any kind of CATE activity on the part of a student. A rationale for this metric is that it includes all types of interactions by users.

Overview of Exams and Course Content

The course associated with this study is specifically for non-majors (i.e., not Electrical Engineering or Computer Engineering majors). The course was offered in a 10-week quarter.

Exam 1 - DC	Exam 2 - Transients and AC
Lectures during weeks 1-5	Lectures during weeks 6-9
• Review basic concepts and units • Series and parallel • Analysis by equivalent circuits • Current and voltage dividers • Mesh analysis • Nodal analysis • Superposition • Thevenin and Norton equivalent models • Maximum power transfer	• Review of capacitors and inductors • Transient analysis • Review of complex arithmetic • Phasor domain analysis • Frequency response (introduction) • Mesh, nodal and analysis by equivalent circuits • AC power and power factor correction
Week 10: Transformers and dependent sources	

Overview of Results

Student performance on a first and second midterm were examined. Results from regression indicates that GPA was a dominant predictive variable for exam scores. On Exam 1 (DC circuits), students using CATE were able to boost their scores above the trend established by the dominant GPA variable. However, this was not the case for Exam 2. The working hypothesis regarding Exam 2, is that more time should be spent on the associated topics and that CATE's coverage of the topics could be improved.

Results from a clustering analysis provided further insights. Clusters were based on CATE usage data and on students' preference for independent vs peer learning. The latter information was collected via surveys; students described the degree to which they worked independently or with peers, and the degree to which they perceived a benefit from CATE or from peer learning.

See Figures 6a and 6b, with scatter plots of students. Students are grouped into clusters and their performance is plotted versus GPA and exam score. On Exam 2, GPA is highly correlated with exam score (0.88). This demonstrates the unfortunate result that students' use of CATE did not allow them to break free of the trend established by GPA. In contrast, students were able to improve their scores on Exam 1, relative to the GPA trend. Note the upper triangular appearance of the scatter plot. These data had a reduced correlation of 0.61. Although these results are disappointing for Exam 2, the data presented here provides an illustrative example of how these analysis techniques respond to both effective and ineffective cases.

Results from Regression Analysis

Regression analysis was used to predict exam scores as a function of cumulative GPA and CATE usage. As shown in Table 1, GPA has the more dominant effect. Of interest is the possibility for CATE to help students outperform the trend established by the more dominant GPA variable for Exam 1. See Table 1 and note that CATE Usage was scaled to a maximum of 4.0, to give it the same dynamic range as GPA. This allowed the weight of the regression coefficients to be compared directly. The class associated with this study had 34 students. Some students opted out, some did not respond to surveys and others were dropped during the outlier removal process (details follow).

Table 1. Results from regression analysis of Exam 1, as reported by R [32].

	Estimate	Std. Error	t value	Pr(>|t|)	Significance
(Intercept)	0.7082	3.4161	0.207	0.83752	
GPA	4.8695	1.0194	4.777	7.32e-05	***
CATE Usage	2.0873	0.7197	2.900	0.00786	**

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Multiple R-squared: 0.493, Adjusted R-squared: 0.4507
F-statistic: 11.67 on 2 and 24 DF, p-value: 0.0002886

Outliers were pruned from the analysis until the Cook's distance for all residual errors was under 0.5. See Figure 3. Note there is some departure from normality in the tails of the residual distribution, as seen in the QQplot. This indicates some level of concern with the results [33], albeit other indicators are sound. For example, the overall p-value for the regression was under 0.001 and the R^2 statistic is around 0.5 (which is considered typical for studies of human behavior [34]).

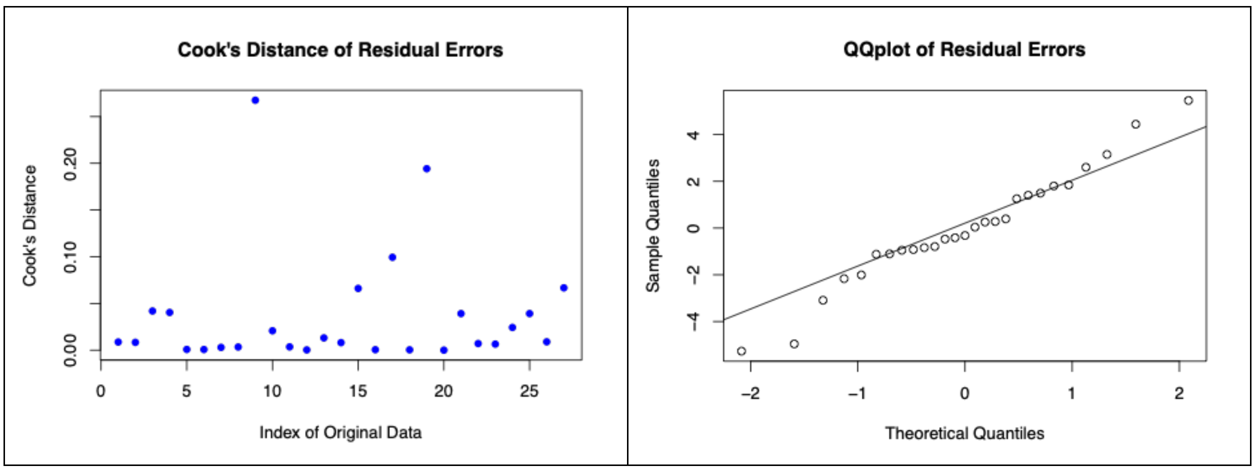


Figure 3. Analysis of residuals of the regression analysis for Exam 1. Outliers were removed such that the Cook's distance was under 0.3. Note there is some departure from normality for the residuals, in the tails of the distribution.

Acknowledging some concern with the QQplot, it is nevertheless interesting to compare the regression coefficients. While GPA is a dominant factor, note the weight for CATE. It is nearly half that for GPA. This speaks to the feasibility of students being able to impact their exam scores via CATE.

Table 2 includes results from regression analysis of Exam 2, as reported by R [32]. Note the p-value on CATE usage indicates that it is statistically insignificant. Thus, CATE usage did not affect the scores for Exam 2. This negative finding is consistent with the results from the clustering analysis. As discussed, more time on Exam 2 topics and expanded coverage within CATE are appropriate areas for improvement.

Table 2. Results from regression analysis of Exam 2.

	Estimate	Std. Error	t value	Pr(>|t|)	Significance
(Intercept)	4.1380	2.2718	1.821	0.0801	.
GPA	4.7849	0.6529	7.328	8.8e-08	***
CATE Usage	-1.1158	0.8692	-1.284	0.2106	

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Multiple R-squared: 0.7079, Adjusted R-squared: 0.6855
F-statistic: 31.51 on 2 and 26 DF, p-value: 1.126e-07

Results for Exam 2 are shown in Table 2 and Figure 4 and indicate that CATE usage was not significant. As seen in Table 2, the coefficient for CATE is negative. This would be a terrible result, but for the lack of significance for the variable! After experimentation and reflection, a working hypothesis has emerged; CATE coverage of the topics associated with Exam 2 needs improvement! Exam 2 covers AC analysis and transients. Plans are to expand practice with complex arithmetic and solving differential equations. Results for Exam 2 were surprising and disappointing. Nevertheless, it was also quite informative regarding important next steps. A clustering analysis followed which has provided greater insight into student performance.

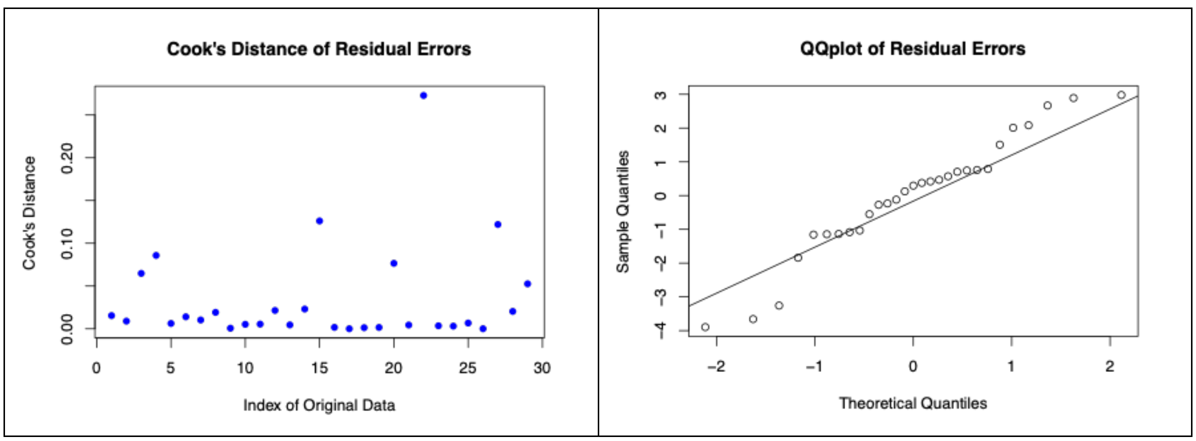


Figure 4. Analysis of residuals of the regression analysis for Exam 2. Outliers were removed such that the Cook's distance was under 0.3. Residuals lack normality as with Exam 1.

Results from Clustering Analysis

Clustering analysis was used to group students based on their preferences for independent or peer learning, their usage of CATE and their exam scores (the analysis of each exam was done separately). Cumulative GPA was not used to form clusters; when included, it overwhelmed the formation process making the interpretation of the cluster characteristics difficult. Rather, GPA data was introduced after cluster formation, so that the average grades for each cluster could be compared. This approach appeared to provide a clearer picture of how CATE usage and learning preference impacted exam scores. Thus, GPA data provided a demographic characteristic for each cluster, as opposed to a variable contributing to cluster formation.

The R package NbClust was used to find the appropriate number of clusters and to assign clusters [35][36]. The "majority rule" technique reported the best number of clusters. This method performs clustering with 26 different methods, over a defined range of clusters (set as 2-10). The compactness of clusters in each case is computed. The optimum number of clusters is found by identifying a knee in the curve where the compactness changes abruptly [35]. The Ward method was used to find the final cluster assignments [37]. Ward is agglomerative. At each step two clusters are merged. The pair merged are the two that increase the within-cluster variance of distances the least [35]. Distances were calculated using a Euclidean 2-norm. The clusters produced were reasonably well separated. See Figure 5. Clusters plotted using the CLUSPLOT package in R [38].

Results demonstrate that students' use of CATE was less beneficial on Exam 2; this is consistent with the regression analysis. As seen in Figure 6b, Exam 2 scores were highly correlated to GPA, with a correlation coefficient of 0.88. On Exam 2, students were not able to alter the GPA-dominated trend by using CATE. In contrast, for Exam 1, students who used CATE more were able to raise their exam scores above the level predicted by a GPA trend. The correlation coefficient demonstrates this quantitatively for Exam 1, reduced to the level of 0.61. Note that one cluster (red squares, Figure 6a) attained higher exam scores across the whole range of GPAs.

Hence, the clustering analysis suggests that students could attain better scores on Exam 1 than the GPA-based prediction. Next, a Wilcoxon ranked sum test [39][40] was performed to see if the differences in exam scores were significant for the various clusters. Wilcoxon yielded a p-value below 0.001, indicating that the difference in means is not zero. This is good news; suggesting that student performance can improve by a significant degree, compared to the trend otherwise expected due to GPA.

Finally, note that a t-test could not be used to compare the means of each cluster. This is because the GPA data was not normal. Wilcoxon has no requirement for normality. It does require similar variances in GPA for the clusters; a Flinger-Killeen test [41] verified the required similarity of variance.

Survey Analysis

A survey was used to gather data on students' learning preferences. It also included a few questions regarding the perceived value of CATE and other learning resources. One question addressed students' agreement or disagreement with the statement "CATE helped discover something misunderstood or unknown to me." Only 1 student out of 28 respondents disagreed; some responses were neutral but 68% expressed some level of agreement.

Table 3. Students' perception of how often various learning resources were useful. Average responses included both peer learners and independent learners. The average for Peer Learning in this table includes independent learners. Hence, results suggest that CATE was more popular than peer learning, when considering all students in the class.

Instructor	CATE	Peer Learning	Google	Textbook
3.32	3.00	2.04	2.00	0.54

Scale: Always = 4, very often = 3, sometimes = 2, rarely = 1, never or not applicable = 0

Students were also asked how helpful they found various resources. Averages appear in Table 3. Use of CATE was ranked higher than both peer learning and Google searches. In these results, all students indicated that CATE was helpful to some degree. One student described CATE as rarely helpful, but all others described it as sometimes, very often, or always helpful.

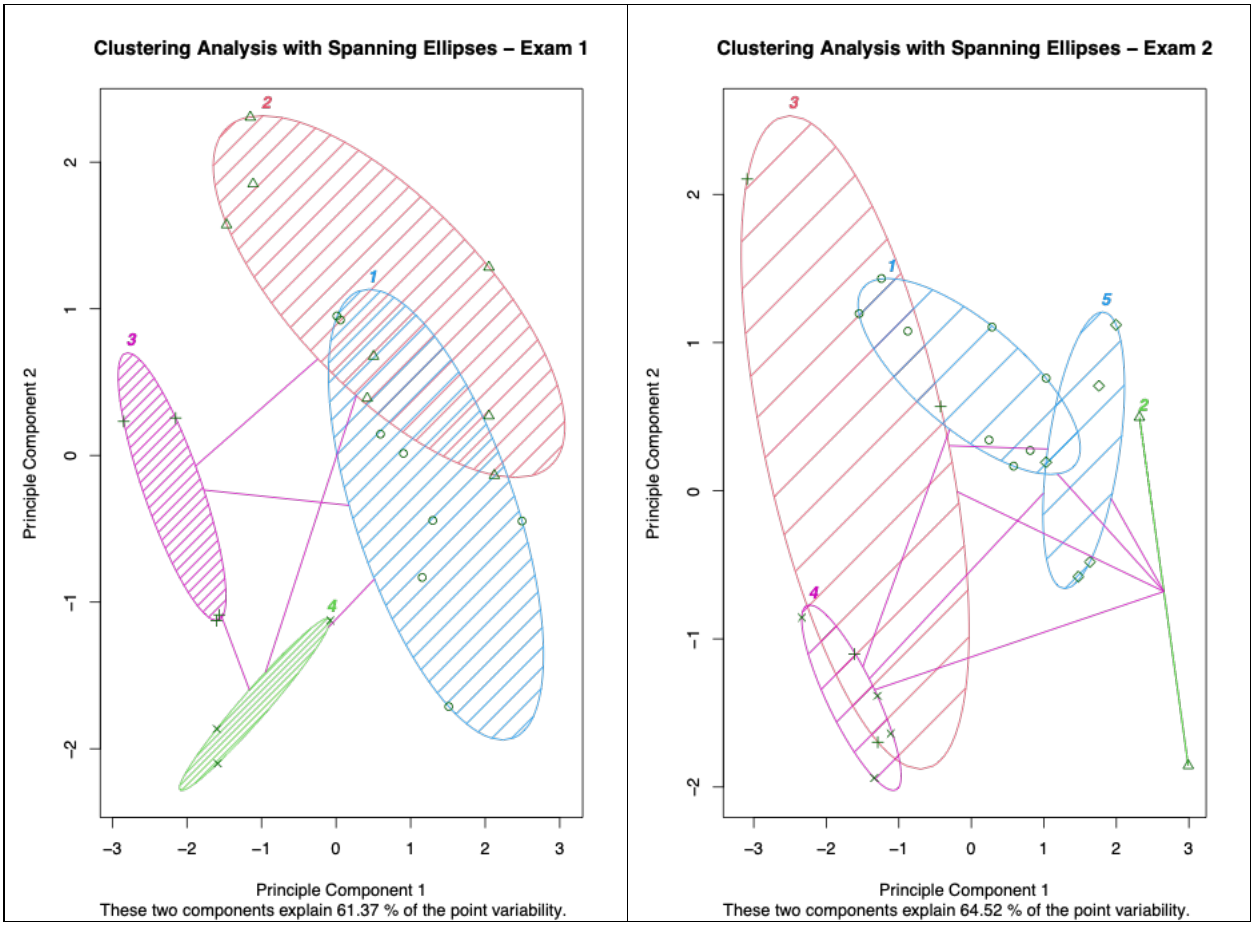


Figure 5ab. Results of clustering analysis. Ellipses are sized to include all points assigned to the associated cluster. Lines interconnect the centroids of each pair of clusters.

Summary of results

- Cumulative GPA is a dominant predictor for exam scores. Hence, it should be included in an analysis, so that any departures from the GPA trend can be observed.
- The CATE usage metric was defined to include any sort of review or practice. Usage was also scaled to a maximum of 4.0, to match the range of GPA values.
- Both regression analysis and clustering suggested that CATE usage helped boost students' scores above the GPA trend, for Exam 1. CATE did not provide a similar benefit for Exam 2 and the working hypothesis is that more time should be spent on these topics and that CATE coverage could also be improved.
- Most students indicated they discovered something misunderstood or unknown via CATE.
- Students ranked CATE as being more helpful than peer learning, Google searches or the textbook.

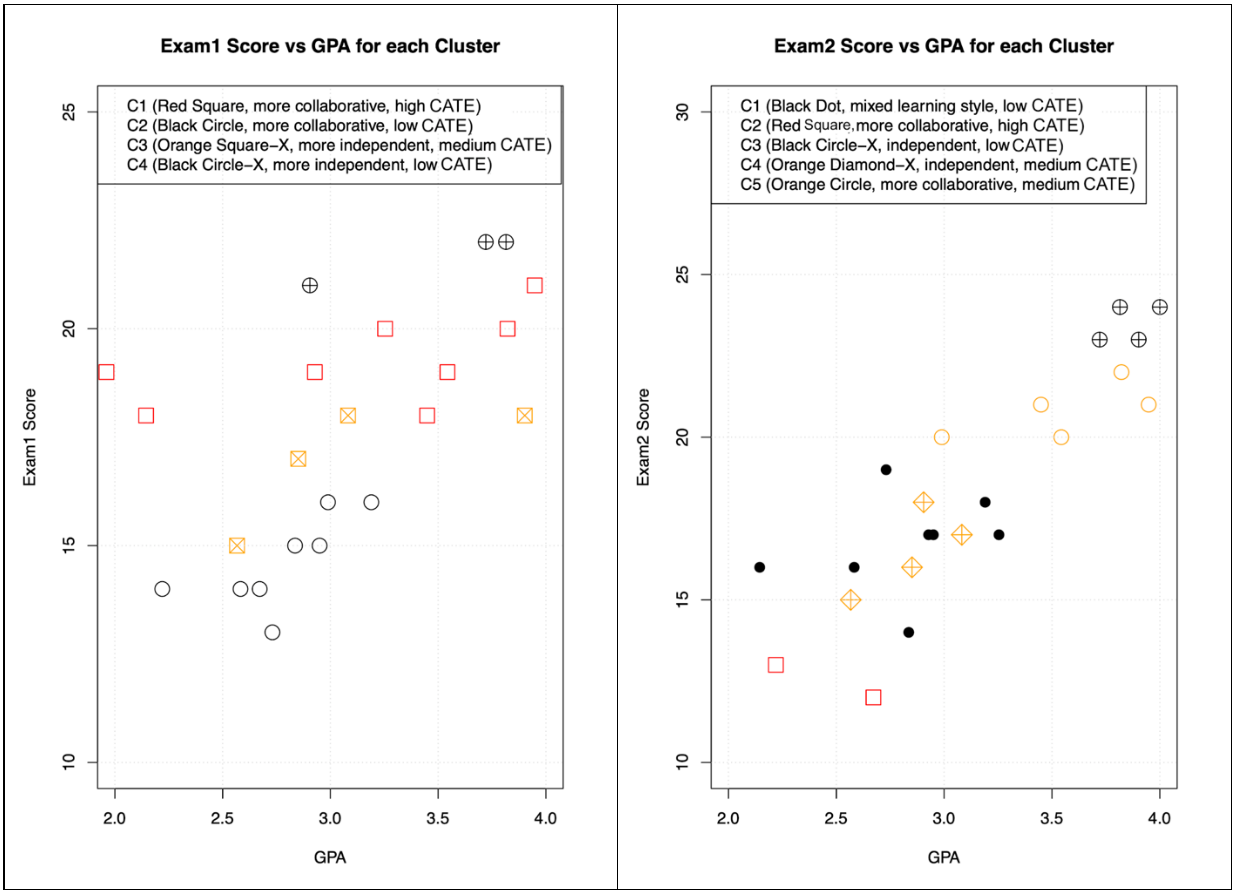


Figure 6ab. Scatter plot with exams scores plotted vertically and student GPA horizontal. GPA was not used to form clusters; it is a demographic variable only. On Exam 1 (a), students were able to improve their scores using CATE, compared to a trend set by GPA. For Exam 2 (b) CATE usage did not help boost scores and the scores were highly correlated to GPA.

The scatter plots of Figure 6 and correlation between GPA and exam score may be useful when gauging the effectiveness of a teaching and learning system such as CATE. First the scatter plots should be upper triangular, indicating that students can raise their scores above the trend established by GPA. Second, the lower the correlation, the better.

What is the future vision for CATE?

Future Expansion of Circuit Topics

1. A top priority for future development is to expand examples and topics associated with the 2nd exam. This includes deeper coverage of prerequisite material associated with complex numbers and solving differential equations.
2. New practice problems are planned that involve breadboarding, to help prepare students for a circuit lab. See Figure 7.
3. Reviewing the CATE usage logs, it appears that a scaffolding feature [42] was hardly used. This is unfortunate as scaffolding can help build connections between topics. It can also promote long-term retention of material [15]. Current plans are to present this feature more prominently on the CATE student interface.

Future Opportunities for Assessment

Mastery grading is a well-established educational practice [43]. In a typical implementation, students are permitted to retake assessments, to demonstrate their abilities. Mastery grading can be time consuming, as it requires additional assessment problems and additional grading. Plans are to modify the CATE quizzing engine to automatically assign new problems and grade them and take advantage of the automated problem generation capability.

Future Opportunities for Automated Tutoring

At present, students' use of CATE is self-directed. Given the capabilities of CATE, it is reasonable to consider a new incarnation as an intelligent tutor [44][45]. These future enhancements would integrate the CATE assessment engine with Google Cloud Services [46], for example, to leverage predictive capabilities involving big data. This approach could help realize individualized tutoring services that recommend practice problems. For example, delving into a root cause issue related to student's mistakes, versus prioritizing newer topics.

Automated tutoring features could help expand the CATE user base. At present, use has focused on students in a course. Thus, CATE provides a supplement to an instructor who serves as the expert guiding students. Alternatively, an automated tutor could provide guidance. This could be helpful for learners who are not enrolled in a course. For example, Knewton integrates big data with education [47] and this service has now been acquired by Wiley [21]. Since the inception of Knewton, services offering predictive analytics that operate on big data are available and can be directly integrated with other systems [46].

Future Opportunities for Educational Research

A shortcoming of this study is its reporting on a single section of a course. Efforts to repeat this study will continue. Beyond this, future development plans include integrating the R statistics package directly with the CATE instructor interface. This would allow other instructors to repeat the analyses presented herein, or modify them, with relative ease.

Future Opportunities Generate Instructional Materials

Student workbooks could readily be generated by drawing from a large question bank. These workbooks could include a set of problems that are customized by an instructor, in terms of the breadth, depth and order of topics. And distinct workbooks could be generated for each student in a class (along with solutions).

Future Expansion of Courses

Results indicate that CATE is beneficial for learning circuits. Future courses under consideration include statics, dynamics, and strength of materials. Anecdotally, students have reacted quite favorably regarding the possibility of a CATE-like system for statics.

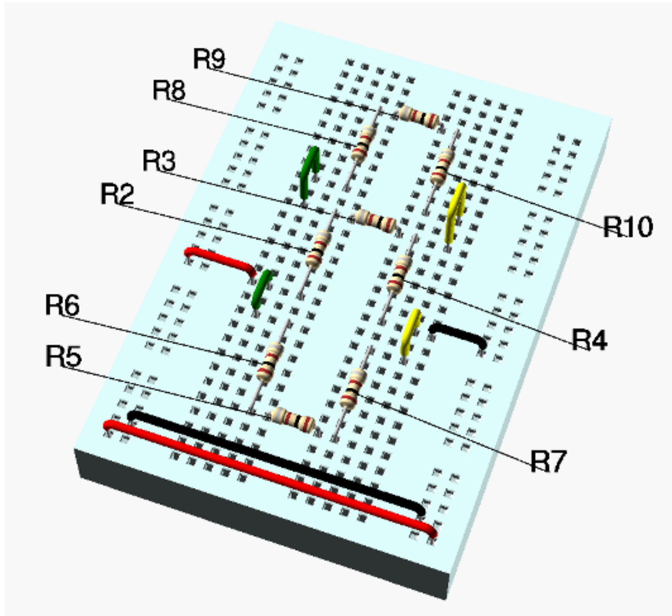


Figure 7. Future work will include learning objectives on breadboarding. For example, asking students to identify the correspondence between resistors in a breadboard vs schematic.

Conclusions

The CATE system is unique in that it generates topologically distinct circuits with step-by-step solutions. And this capability is integrated with a web-based system that offers examples, practice and quiz problems. Results indicate that students who use CATE can improve their exam scores, thus breaking from a trend that is dominated by GPA. Many options are possible in the future, including additional learning objectives in circuits, as well as whole new courses.

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