

# Conceptual-Based Writing Exercises in a Circuit Analysis Course

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**Abstract—Contribution:** This article describes the implementation, assessment, and evaluation of conceptual-based writing exercises in an introductory course on electric circuit analysis.

**Background:** Students' struggles in gateway courses such as circuit analysis are often traced to inadequate metacognitive skills on the part of the student as well their misconceptions regarding fundamental phenomena related to the course. Writing is known to be a powerful tool for insight into a student's thought process and to foster metacognitive activity.

**Research Questions:** What effect does the use of short writing exercises have on students' understanding of fundamental concepts related to the behavior of electric circuits operating at dc? What effect does the use of the conceptually based writing exercises have on students' ability to justify their responses when answering conceptual questions related to basic electric circuit concepts?

**Methodology:** In the first semester of the study, a single writing exercise was given and in the second semester, a total of five such exercises were administered. In each semester, students were separated into "at-risk" and "not at-risk" groups based on their responses to the first writing exercise. A  $2 \times 2 \times (2)$  mixed analysis of variance (ANOVA) was conducted, with at-risk/not at-risk and semester/semester between-subjects factors and pre-test/post-test on a multiple-choice conceptual-based exam a within-subjects factor.

**Findings:** Results suggest that only the at-risk group may have benefited in terms of deepened conceptual understanding and the ability to justify their responses from the use of multiple conceptual-based writing exercises.

**Index Terms—**Circuit analysis, education, metacognition, misconceptions, self-regulated learning, writing.

## I. INTRODUCTION

CIRCUIT analysis is typically the first calculus-based and discipline-specific course for electrical and computer engineering majors. It is often considered a gateway course to these disciplines, and while the reasons why students may

struggle in such a course are many, often it is the study skills pertinent to the collegiate environment that students lack [1]. As described in [2], students who struggle in gateway courses often interpret their difficulty as primarily content-related rather than to reflect the need to modify their approach to the learning process in general. This disconnect between students' perceptions of their struggles and the actual cause of their difficulty in a gateway course such as circuit analysis may be traced to underdeveloped metacognitive awareness. An example of this is the tendency of many struggling students to rely exclusively on formula memorization and pattern matching. While memorizing basic relations, such as Ohm's law and Kirchhoff's circuit laws, and learning to properly follow algorithms such as the node voltage method are required in circuit analysis courses, as pointed out in [3] students who need to strengthen metacognitive skills often equate their casual familiarity with vocabulary words to content mastery. Therefore, in addition to memorizing common formulas, vocabulary, and algorithms, understanding their origin, meaning, and proper application is vital for success in a course such as electric circuit analysis.

Research has demonstrated that proficient learners not only demonstrate an ability to accurately assess their understanding of the material but also to monitor and direct their learning efforts toward a desired outcome [4]. Pintrich [5] identified these skills as two dimensions of metacognition, namely, "knowledge of cognition" and "regulation of cognition." Thus, to be a skilled learner, the student must be able to accurately identify gaps in their understanding (i.e., exhibit knowledge of cognition) and to be able to devise, follow, and adjust their approaches to close their knowledge gaps (i.e., exhibit regulation of cognition). These skills together describe the self-regulated learner [6], [7].

A second significant impediment to a student's mastery of the content in gateway courses is inaccurate prior knowledge [8]. The constructivist theory of teaching and learning illuminates the role of prior knowledge in the learning process as the theory posits that a student's prior knowledge, preconceptions, and beliefs serve as filters in processing new information [9]. In gateway courses, it seems that often student preconceptions may in fact be misconceptions. As described in [10], for example, it has been found that students entering courses on statistics often have intuitions regarding probability and statistics that are in opposition with accepted reasoning. Likewise, it has been found that the novice in a course on circuit analysis may employ mental models that are contrary to the accepted scientific understanding of electrical phenomena

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and that these erroneous models may impede student mastery of basic circuit analysis. Some misconceptions may be relatively easy to vanquish, others in the electrical circuit domain are considered “robust” [11], and thus more resistant to change. For example, belief that a battery is a source of constant current, belief that current is consumed, and belief that current “flow” is a sequential process are often cited misconceptions [12]–[17]. Interestingly, textbooks in electric circuit theory may foster such misconceptions through the use of inconsistent models and analogies [17]. The approach taken in this work to address both the issues of inaccurate prior knowledge and underdeveloped metacognitive skill among beginning students in electric circuit analysis is to explore the use of short-answer conceptual-based writing exercises that force students to confront problems that elicit common misconceptions and to do so without simple reliance of memorized formulas.

There is significant literature across STEM fields describing how misconceptions can be readily uncovered through the examination of student writing. For example, the use of short in-class writing exercises in the teaching of a general chemistry course [18] has been noted to be an effective means to identify student misconceptions pertaining to basic thermodynamic principles. Kitto [19] found that student misconceptions regarding materials science were readily identified by having students compose a research paper that required not only an analysis of materials properties but also justification as to why certain materials should be used in a given product. As described in [20], biomedical students in a pathology course were instructed to compose questions regarding disease mechanisms that centered on conceptual understanding rather than factual knowledge. The questions were examined by expert pathologists and found to be an effective vehicle for identifying examples of misconceptions. In using writing assignments within an introductory physics course, Hein [21] contended that student misconceptions are more readily revealed in such assignments as opposed to within traditional measures such as exams. Similar examples of using writing as a key tool in identifying student misconceptions include those in mechanical engineering [22], [23] and mathematics [24].

While it appears clear that writing exercises may be used to uncover student misconceptions in a variety of STEM fields, what evidence is there that writing can help improve student performance? Hanson and Williams [22] described the use of “explain-a-problem” written assignments to enhance self-assessment and communication skills among undergraduates in an introductory statics class. While the explain-a-problem approach was found to aid students in achieving the self-assessment objectives of the assignment, improvement in student learning was not observed [22]. Venters *et al.* [23] adapted the explain-a-problem approach in implementing “process problems” in a statics course at another institution but with a focus on effecting conceptual change. In the process problem approach, one problem from the nearly weekly assignment set was assigned in which students were to explain both the objective of the problem and the steps they used to complete the objective. Like Hanson and Williams,

Venters *et al.* [23] found that when using conventional testing that tends to favor procedural knowledge, differences in the student performance due to the process problems were not observed. When considering pre-/post-test scores from a Statics Concept Inventory, however, a significant difference ( $p = 0.001$ ) was found favoring the group of students completing the process problems over a control group that did not. Halim *et al.* [25] found that writing exercises were not only useful in identifying misconceptions of students studying introductory biology but also when coupled with peer review and revision, the writing exercises could be used to correct student misconceptions.

Nückles *et al.* [26] considered the use of various cognitive and metacognitive prompts in having students in a psychology course compose written learning protocols after watching a videotaped lecture. Examination of pre-test/post-test comprehension test results indicated that metacognitive prompts improved learning outcomes. Improved learning outcomes with writing exercises that include metacognitive prompting is consistent with Bangert-Drowns *et al.*’s review of hundreds of articles that described various writing-to-learn approaches [27]. Therefore, beyond its utility in identifying student misconceptions, when writing exercises incorporate both cognitive and metacognitive aspects to promote reflective thinking on the part of the student, the learning process is enhanced [25]. Improvement of student outcomes through the implementation of writing activities appears most impactful in deepening conceptual understanding.

## II. PURPOSE AND RESEARCH QUESTIONS

The purpose of this study was to investigate the impact of short answer writing exercises that included metacognitive prompts on the conceptual understanding of undergraduate students in an introductory course on circuit analysis. As with the work of Venters *et al.* [23], assessment measures consist not of common course exams that focus on formulaic problem solving, but rather on demonstration of conceptual understanding. The two overarching research questions to be addressed in this work are as follows.

- 1) As suggested by their scores on a conceptual-based multiple-choice exam, what effect does the use of short writing exercises have on students’ understanding of fundamental concepts related to the behavior of electric circuits operating at dc?
- 2) What effect does the use of the conceptually based writing exercises have on students’ ability to justify their responses when answering conceptual questions related to basic electric circuit concepts?

As described below, these two questions are addressed for two groups of students, those deemed to be at-risk for failing the course and those not at-risk.

## III. METHODS

### A. Description of the Course and Students

The course in question is a sophomore-level required course (EELE 201) on electric circuit analysis for electrical and computer engineering majors at Montana State University. The

course covers basic circuit quantities, node and mesh current methods, circuit theorems, operational amplifier basics, the complete response of first-order circuits, sinusoidal steady-state analysis, ac power, and ideal transformers. Prerequisites for the course include calculus II and EELE 101. EELE 101 is a semester-length course that serves as a gentle introduction to the disciplines of electrical and computer engineering through a weekly lecture and a weekly lab. Upon leaving EELE 101, students will have had their first exposure to the circuit-related concepts of voltage, current, resistance, series and parallel resistor combinations, Ohm's law, KVL, and KCL as well as an introduction to fundamental programming concepts.

### B. Writing-Based Conceptual Exercises

All writing-based exercises used in this study had the same form. Each exercise consisted of one circuit schematic and a primary question related to the circuit when operating at dc. After the initial question was posed, but prior to answering the question, students were asked to rate their perceived understanding of the question and their perceived ability to correctly answer the question. These self-assessment questions were asked again after the student completed their response to the primary question. Finally, the following two tasks were posed.

- 1) Read through your response. Identify the sentence from your response with which you have the least confidence and explain why you question its accuracy.
- 2) Read through your response. Identify the sentence from your response with which you have the most confidence and explain why you are convinced of its accuracy.

The tasks posed beyond the primary question were meant to spur metacognitive activity. Students were given approximately 20 min to complete a given writing exercise. After 20 min, the instructor collected all of the exercises and spent approximately 10 min describing a proper way to address the exercise's primary question. During this explanation, the instructor would identify one or two common misconceptions that students often exhibited in their response to the question. The written exercises, which served as quizzes, were never returned to the students. The initial writing exercise used in this study and described in [28] and [29] is provided in the Appendix.

As described in [28], the original intent of this first writing exercise was to serve as a means to identify students likely to struggle in the course. The initial writing exercise was scored on a five-point holistic scale that considered not only the correctness of the response but also the logic and quality of the required justification of the response. Students scoring at the low end of the conceptual-based writing exercise were found, weeks later, to struggle on the course's first exam. In this work, we define students scoring either a one or a two (one being the lowest possible score) to be in the at-risk class. Students scoring above this are defined as not at-risk. A discussion on the most common misconceptions exhibited among students responding to the initial writing quiz as well as the prospects of using natural language processing (NLP) techniques to automatically identify such misconceptions may be

found in [30]. The additional writing quizzes used for this study required students to demonstrate their understanding of how to apply the ideal models of such elements as independent voltage and current sources, voltmeters, ammeters, and short and open circuits. It should be emphasized that none of the writing questions were computation-based but rather required the student to articulate through written explanation conceptual understanding of the behavior of simple electric circuits operating at dc.

Results from two semesters in which the writing quizzes were utilized are presented. In the fall 2019 semester, one writing quiz was administered during the fifth class period of the semester. In the fall 2020 semester, the same writing quiz (that found in the Appendix) was again given during the fifth class period. While in the fall 2019 semester, only this single writing quiz was administered, during the fall 2020 semester, four additional quizzes were given prior to the first exam. Students in the fall 2019 semester thus served as the control group and those in the fall 2020 semester served as the experimental group.

### C. Assessing Conceptual Understanding

To assess potential gains in conceptual understanding of fundamental concepts regarding the behavior of electric circuits, the 29-question multiple-choice Determining and Interpreting Resistive Electric Circuits Concepts Test (DIRECT) 1.0 exam [12] was used in a pre-test/post-test fashion. The DIRECT 1.0 was developed to provide instructors teaching the analysis dc electric circuit a means to probe students' conceptual understanding much the same as the force concept inventory (FCI) is used by instructors teaching Newtonian physics [31].

The objectives of the developers of the DIRECT 1.0 included addressing physical aspects of dc electric circuits, as well as concepts related to energy, current, and potential difference. Content validity of the DIRECT 1.0 was established through the use of an independent panel of experts to match test questions to objectives. During the development of the DIRECT 1.0, when the panel found low agreement between objectives and questions, the questions were rewritten. Construct validity of the DIRECT was evaluated through factor analysis and interviews with students who completed the exam. The reliability of the DIRECT was evaluated using the Kuder–Richardson formula (KR-20). The KR-20 score of 0.71 for the DIRECT 1.0 met the 0.70 threshold for group measurements [12].

The questions of the DIRECT 1.0 were designed for use with both high school and college students and include common misconceptions embedded into the question distracters. In the article describing the DIRECT 1.0, correlation, discrimination, and difficulty measures are given for the 29 questions based on the results from 1135 students ( $n = 454$  high school students and  $n = 681$  university students). A second version of the DIRECT, the DIRECT 1.1 is also described in [12]. This second version is more quantitative leading the developers to recommend the DIRECT 1.0 to be used when a measure of conceptual understanding is sought as is the case in the present study.

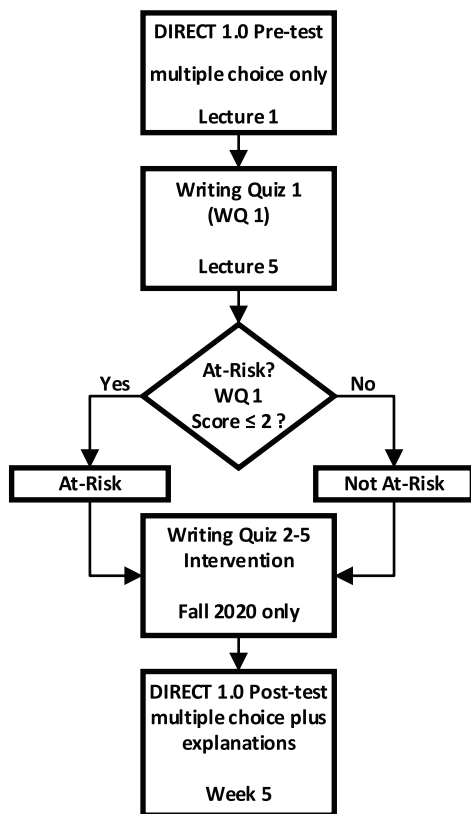


Fig. 1. Flowchart of the experimental procedure. The intervention, writing quizzes 2–5, were only administered to the 2020 cohort. The DIRECT 1.0 post-test was given days before the course’s first standard exam.

In all cases within this study, students completed handwritten versions of the DIRECT 1.0 during class time. The DIRECT 1.0 exams were never returned to students, nor the results shared with them. The DIRECT 1.0 was administered on the first day of class (pre-test) and again just prior to exam 1 (post-test) to all participating students. Since exam 1 occurs in the fifth week of course, the post-test DIRECT 1.0 score was recorded approximately one-third into the semester. To provide insight into the ability of students to justify their responses to conceptual questions, the post-test version of the DIRECT 1.0 was augmented to require students to justify their answers to 18 of the quiz’s 29 questions. Five of the DIRECT 1.0 exam’s questions have students pick a potential explanation to an observed electric phenomena. For example, one question asks the student to choose from four possible explanations as to why lights in the home come on almost instantaneously. Since these five questions had students pick an explanation, the questions were not included in the 18 selected for students to include a written justification. The remaining six questions that were not included in the 18 had to do with circuit layout (e.g., series versus parallel combinations and which layout will light an incandescent bulb). The 18 questions chosen for students to justify were therefore those deemed well suited for requiring meaningful justification.

Shown in Fig. 1 is a flowchart illustrating the elements and timing of the assessment items used in this study. As suggested in the flowchart, while the control group (Fall 2019) took

TABLE I  
MEANS AND (STANDARD DEVIATIONS) OF PRE- AND POST-TEST  
DIRECT 1.0 SCORES

| Control Group      | Fall 2019 At-risk (n = 30) |              | Fall 2019 Not at-risk (n = 22) |              |
|--------------------|----------------------------|--------------|--------------------------------|--------------|
|                    | Pre-test                   | Post-test    | Pre-test                       | Post-test    |
| Mean (SD)          | 14.13 (3.97)               | 19.83 (4.43) | 18.45 (4.50)                   | 23.36 (3.90) |
| Experimental Group | Fall 2020 At-risk (n = 18) |              | Fall 2020 Not at-risk (n = 19) |              |
|                    | Pre-test                   | Post-test    | Pre-test                       | Post-test    |
| Mean (SD)          | 14.22 (4.05)               | 22.22 (3.12) | 17.58 (4.80)                   | 23.47 (3.27) |

only the initial writing quiz, the experimental group (Fall 2020) took four writing quizzes in addition to the initial writing quiz.

#### IV. RESULTS

Gathered in Table I are the data pertaining to the pre- and post-DIRECT 1.0 scores for both the at-risk and not at-risk populations of the control group (2019) and experimental group (2020). The DIRECT is scored out of 29; both the mean and standard deviations are given.

The analysis strategy was to conduct a  $2 \times 2 \times (2)$  mixed analysis of variance (ANOVA), with at-risk/not at-risk and 2019/2020 between subjects factors and pre-test/post-test a within-subjects factor. The mixed design with two between-subjects factors and one repeated measure was used because it provides a single analysis that tests main effects and interactions between levels of the between and within factors, and, because participants act as their own controls, the design works well with smaller samples. Our data satisfied all five of the principal assumptions to be met for a valid analysis: 1) the independent variables were categorical, and the dependent variables were interval; 2) the four groups who participated over the two years were independent of each other; 3) the difference scores in the dependent variables (i.e., post-test minus pre-test) were normally distributed for each group as indicated by nonsignificant Shapiro–Wilk tests and by inspection of Q–Q plots; 4) no significant outliers were identified; and 5) Levene’s test and Box’s M test were both nonsignificant, indicating the homogeneity of variance. Because of the exploratory nature of this pilot study, the alpha level for the following analysis was set at 0.10. Various follow-up statistical tests within and across semesters are reported below to answer the following questions regarding the statistical significance and effect size of observed differences between groups based on their mean DIRECT 1.0 scores.

*Question 1:* Is there a statistically significant difference in the performance on the DIRECT 1.0 pre-test between the at-risk group and the not at-risk group within the same semester?

*Response:* An ANOVA with at-risk/not at-risk and 2019/2020 as between-subjects factors and the pre-test DIRECT 1.0 as the dependent variable showed only a significant main effect for at-risk/not at-risk,  $F(1, 85) = 17.00$ ,  $p < 0.001$ , with partial eta squared ( $\eta_p^2$ ) = 0.17 (Cohen [32]

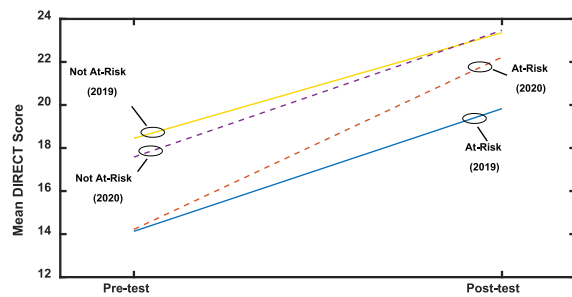


Fig. 2. Comparison of at-risk and not at-risk groups of pre-and post-test scores for the 2019 and 2020 years. Additional writing quizzes were administered in 2020 and functioned as an intervention.

suggested 0.01, 0.06, and 0.14 as small, medium, and large effect sizes, respectively). This result provides strong support that for both years the at-risk groups scored significantly lower than the not at-risk groups, indicating that the writing quiz is a useful means to identify students likely to have trouble with the conceptual elements of the course content.

**Question 2:** Is there a statistically significant difference between the at-risk and not at-risk groups in their pre-test and post-test performance on the 2019 and 2020 DIRECT 1.0?

**Response:** A mixed ANOVA was conducted with at-risk/not at-risk and 2019/2020 as between-subjects factors and pre-test/post-test DIRECT 1.0 scores as the within-subjects factor. There was a large significant main effect for DIRECT 1.0 score,  $F(1, 85) = 239.460$ ,  $p < 0.001$ , with  $\eta_p^2 = 0.74$  and a significant interaction between DIRECT 1.0 scores and year  $F(1, 85) = 4.305$ ,  $p = 0.04$ , with  $\eta_p^2 = 0.05$ , but importantly, there also was a significant interaction between DIRECT scores and at-risk/not at-risk groups,  $F(1, 85) = 3.345$ ,  $p = 0.07$ , with  $\eta_p^2 = 0.04$ . Further analysis for the source of the interaction is displayed in Fig. 2. The two at-risk groups and the two not at-risk groups did not significantly differ in their respective pre-test scores for 2019 and 2020; however, for the post-test scores, there was a significant difference between the groups. The not at-risk groups showed no significant difference between 2019 and 2020, but the at-risk groups showed a significant difference, with the 2020 post-test scores greater than the 2019 post-test scores. This indicates that while the fall 2020 intervention (additional writing-based quizzes) did not have a significant impact on the post-test scores of the not at-risk groups, the intervention had a statistically significant impact on the post-test scores of the 2020 at-risk group. An attempt to meaningfully interpret this result is detailed in Section IV.

**Question 3:** While a statistically significant difference in the post-test scores of the at-risk groups from fall 2019 and fall 2020 has been observed, what is the effect size of the difference between the means using Cohen's  $d$ ?

**Response:** The Cohen's  $d$  effect size for unequal sample sizes [32], [33] was calculated in comparing the post-test means on the DIRECT 1.0 for the fall 2020 at-risk group ( $M = 22.22$ ) to that of the fall 2019 ( $M = 19.83$ ) at-risk group. The effect size was found to be 0.60, a medium effect size as noted in Table II (raw score). Using Cohen's U3 index, we calculated an Improvement Index with the 0.60 effect

TABLE II  
COMPARISON OF SECOND-ATTEMPT DIRECT 1.0

|                         | Not At-Risk |           | At-Risk            |           |
|-------------------------|-------------|-----------|--------------------|-----------|
|                         | Fall 2019   | Fall 2020 | Fall 2019          | Fall 2020 |
| <b>Raw Score Mean</b>   | 23.36       | 23.47     | 19.83              | 22.22     |
| <i>p</i> -value         | $p = 0.922$ |           | $p = 0.034$        |           |
| Effect Size             |             |           | Cohen's $d = 0.60$ |           |
| <b>Explanation Mean</b> | 1.78        | 1.82      | 1.58               | 1.73      |
| <i>p</i> -value         | $p = 0.370$ |           | $p = 0.007$        |           |
| Effect Size             |             |           | Cohen's $d = 0.77$ |           |

size [34]. The Improvement Index was 23%, which translates to a U3 index of 73%, indicating that 73% of the at-risk students who received additional writing-based quizzes scored above the mean score of those who did not.

**Question 4:** Is there a statistically significant difference between students who engaged in five writing-based quizzes to justify their responses when answering conceptual questions related to basic electric circuit concepts and students who engaged in only one, and if so, what is the corresponding effect size that may result from this intervention?

**Response:** To explore the ability of students to *justify* their reasoning with regard to several concepts pertinent to dc circuit analysis, in both the fall of 2019 and the fall of 2020 semesters, the post-test version of the DIRECT 1.0 was augmented to require students to justify their answers to 18 of the quiz's 29 questions. The 18 questions chosen for students to justify were those deemed well suited for requiring meaningful justification. In addition to the raw scores on the pre-test and post-test scores as presented previously, the "quality" of the students' justifications for each of the 18 "justification questions" they answered *correctly* was scored. The quality of the students' justifications was evaluated using a three-score rubric. A score of "0" indicated that while the correct multiple-choice option was selected, the student's rationale for the selection suggested that the answer was almost certainly a guess. In other words, the student's explanation did not properly justify the response. A score of "1" was given when the student's justification of the response suggested he/she had some understanding of the underlying concept and their choice of options was likely not a guess. Finally, a score of "2" was reserved for those responses that clearly indicated the student had a true understanding of the underlying concept as revealed through a convincing justification. At-risk and not at-risk groups were analyzed separately and independent samples  $t$ -tests were used to determine whether observed differences in the mean scores were statistically significant. The results are shown in Table II. Although the data are ordinal in nature, the data for each year for at-risk and not at-risk students was analyzed separately for normality. All distributions were within acceptable values for skewness and kurtosis. In addition to the parametric  $t$ -tests, we also conducted nonparametric Mann-Whitney  $U$  tests for independent samples to support results from the independent samples  $t$ -tests. Results from the Mann-Whitney  $U$  tests supported a significant difference for the at-risk group ( $p = 0.023$ ) and a nonsignificant difference for the not at-risk group ( $p = 0.327$ ).

The explanation means of Table II shows that once again the 2019 and 2020 not at-risk students appear to have performed similarly, this time in terms of the quality of their explanations (nonsignificant difference); however, the at-risk students in fall 2020 performed at a higher level than their 2019 counterparts and the observed difference is statistically significant, with an effect size of 0.77. Using Cohen's U3 index, we calculated an Improvement Index with the 0.77 effect size [34]. The Improvement Index was 28%, which translates to a U3 index of 78%, indicating that 78% of the at-risk students who received additional writing-based quizzes had an Explanation score above the mean score of those who did not. But what do effect sizes of 0.60 and 0.77 suggest? While by Cohen's initial guideline [32], 0.60 would fall within the medium effect size range and 0.77 nearly at the large range, there is no standard way to characterize across disciplines whether a given effect size is small, medium, or large. It is perhaps useful to consider the meta-analysis of Hattie [35] in which the effect sizes of more than 250 influences on student achievement were ranked according to the observed effect size. A factor identified in Hattie's meta-analysis as falling into the, "potential to considerably accelerate student achievement" class are conceptual change programs (0.99). Such programs recognize the role that student misconceptions have in hindering student achievement and implement strategies to foster conceptual change. Hattie also identifies various strategies that foster metacognition and self-regulated learning to fall in either the "potential to considerably accelerate student achievement" or "potential to accelerate student achievement" categories. Our observed effective sizes of 0.60 and 0.77 are above Hattie's 0.40 "hinge point" and fall into the categories just defined when considered with the at-risk population in EELE 201.

## V. DISCUSSION

From the data presented, it appears that while the additional short answer questions received by the fall 2020 students did not have an impact on the conceptual knowledge of the not at-risk group, at least as measured by the DIRECT 1.0, they appear to have had a notable effect on the at-risk group. Recall that the at-risk/not at-risk groupings were made based on the scores of students on the initial writing exercise given during the fifth period of EELE 201. The at-risk class was made up of students scoring either a one or a two on the five-point holistic scale. Scores of one or two did not necessarily mean a student exhibited a misconception, but rather the response may have been entirely superficial, not addressed the question, or have been marked by faulty logic. While responses scoring a four or five would not have any indication of a misconception, it was possible that a score of 3 is given to a response with a noticeable misconception. In such a case where the answer was based on a faulty model but the justification "demonstrated sound logic and clear metacognitive activity," it could be scored a 3 [28]. In other words, the separation between the at-risk and not at-risk groups was not purely based on observed misconceptions or correctness of response but also considered the degree to which the response demonstrated meaningful

thought on the question. Of course, as suggested in the pre-test performance on the DIRECT 1.0, in general, the at-risk group was characterized by more misconceptions.

In addition to an improved raw score of the at-risk experimental group on the post-test version of the DIRECT 1.0 as compared to the at-risk control group, the at-risk experimental group also displayed an improved ability to justify their responses on the DIRECT 1.0 suggesting again, a deeper conceptual understanding by the at-risk experimental group.

It is hypothesized that the key reason why the conceptual-based writing exercises appear to have a notable impact on at-risk students are that the exercises encompass elements of conceptual change programs and tend to promote deeper metacognitive processes than basic computation problems. While students falling into the not at-risk group may exhibit common misconceptions regarding the behavior of electric circuits upon entry to the class, it is speculated that such students tend to possess the metacognitive skills to both accurately assess their understanding and to devise and follow effective plans to close their knowledge gaps. On the other hand, it may be the case that the at-risk class tends to contain students lacking these critical metacognitive skills and that the writing exercises help these students begin to develop them in ways that standard computation-based problems do not. Indeed, a course such as electric circuit analysis requires students to apply various algorithmic processes (e.g., node voltage method) that do not require a strong conceptual understanding and exams often reflect the primarily computation-based nature of such courses.

These interpretations appear to be consistent with similar studies in the literature. For example, in reflecting upon the improved post-test performance on the statics concept inventory of students completing "process problems" that had students write out the objective of a standard homework problem and the steps used to complete it, the authors write, "it is possible that the writing assignments may have prompted students to metacognitively reflect on their own understanding of course concepts, thus strengthening their understanding..." [23, p. 13]. This is consistent with the observations of Klein [36, p. 203] in that when reviewing the impact of writing on learning notes "that metacognitive writing prompts are a moderator variable that reliably increases the effect of writing on learning."

It is instructive to consider a couple of examples of student responses to the metacognitive prompts. Take for instance a student's response to question #6 of the first writing exercise (see the Appendix). In the response to the main question (i.e., #3), this student expressed that, while the current in  $R_2$  and  $R_3$  would be affected by a decrease in  $R_2$ , the potential difference across those resistors would stay the same. In reflecting on this response in answering the metacognitive prompt of #6, the student questions this original assertion: "I have the least confidence in claiming all the voltages remain the same because I assume voltages won't change due to a drop in resistance since the total potential drop has to be zero but am not 100% on how to explain that. But if  $I_3$  drops and  $R_3$  remains the same then  $V_3$  drops." This student realizes that there is a contradiction

in his earlier claim that the voltage drop across  $R_3$  does not change if at the same time he suggests that the current in  $R_3$  does change while the resistance of  $R_3$  remains constant. Clearly, this student is using the metacognitive prompt and ensuing reflection to alter his understanding of the workings of the circuit. Students who consistently use such metacognitive skill are more likely to adjust their thinking when appropriate and arrive at a more accurate understanding of the operation of a circuit.

The metacognitive prompts may also be used to identify students who hold a particular misconception rather strongly. Take for instance the response of a student who exhibits a “sequential” misconception in response to #3, in this case, expressing that changes in voltage and current in the circuit only occur at the location of  $R_2$  and after. In reflecting on his response as required in #7, he states he is most confident that the potential difference and power do not change between  $V_s$  and  $R_1$  as, “that spot has not been affected by the changing resistance yet so everything before the second node would remain the same.” It is likely, especially for cases in which a misconception is held tightly that more powerful results may be achieved with the writing exercises if personalized feedback is implemented.

In this study, the feedback process has been for the instructor to discuss a given writing exercise with the entire class immediately after the students hand in their work. Furthermore, the exercises have not been returned. Clearly, feedback has not been personalized. Feedback is known to elicit a significant effect size benefit in terms of student achievement [37] particularly when it is personalized. As used in the current study, the writing exercises effectively addressed likely only one of the two processes that Chi [11] notes as important for overcoming robust misconceptions. While the metacognitive prompts and limited feedback likely helped students recognize when a shift in their conceptual structures was necessary to conform to proper understanding, targeted feedback would be more effective to help most students build proper schema.

The fact that only the at-risk group appeared to benefit from the additional writing exercises is an intriguing result. It is believed that the not at-risk group came to the course with sufficiently developed metacognitive skill to be able to overcome many misconceptions they may have had upon entry into the class without the intervention while the intervention helped the at-risk class strengthen their underdeveloped metacognitive skill. Using measures other than the DIRECT 1.0 might illuminate whether the writing exercises helped both groups in some manner.

While the intervention consisted of four additional writing exercises, the question remains as to whether this number is sufficient or if increasing the number of writing exercises would have a greater effect. It would also be interesting to study whether student responses to the metacognitive prompts become richer with additional writing exercises. For example, when responding to question #7 asking for their most confident sentence, a significant number of students went to formulas with which they were comfortable as in the following two responses to question 7.

- 1) “I am confident in my sentence saying that power is a function of current and voltage. I am confident because I remember the equation  $P = VI$ .”
- 2) “I am confident in anything that involves ohm’s law or the power equation. I like equations, they do not lie or try to trick you. If  $I = V/R$  and  $R$  gets smaller mathematically  $I$  will get bigger.”

Weaning students from an almost exclusive focus on equations and helping them acknowledge the assumptions they are making in using them (e.g., that the student with comment (2) is assuming that  $V$  remains constant which in fact may not be the case) may come with additional writing exercises and with grading emphasis placed on conceptual understanding.

The potential weaknesses of the present study include the use of two cohorts of students instead of a single one and the relatively small sample sizes involved. Each semester, only one lecture section of EELE 201 is offered. Since the writing exercises were administered during lecture periods, it would have been awkward to split a given cohort into experimental and control groups. In the future, if the writing exercises are given online with automatic feedback as suggested in [30], carrying out such an experiment with a single cohort is possible. While acknowledging this potential weakness, both cohorts in the existing study were subject to the same course prerequisites and were found to have performed similarly on the pre-test. For these reasons, using two cohorts is not viewed as a serious risk to the validity of the results. The total population in this study is 89 (48 at-risk and 41 not at-risk). This population reflects only first-time students in the class who took both the pre- and post-tests as well as all writing quizzes offered. The mixed ANOVA used here was appropriate to identify the main effects and interactions between levels of the between factors and repeated factor. This analysis met all the assumptions for a repeated measures ANOVA, and because participants act as their own controls, the analysis works well for smaller samples.

## VI. CONCLUSION

Short-answer conceptual-based writing exercises were administered during class time in a sophomore-level course on circuit analysis with the intent of promoting deeper conceptual understanding and metacognitive activity. Based on their scores on the first writing quiz, students were placed into either the at-risk or not at-risk to fail groups. In answer to the first research question (i.e., As suggested by their scores on a conceptual-based multiple choice exam, what effect does the use of short writing exercises have on students’ conceptual understanding of fundamental concepts related to the behavior of electric circuits operating at dc?), the results suggest that while four additional writing quizzes did not appear to improve the performance of the not at-risk group, the experimental at-risk group outperformed their at-risk control counterpart on a 29-question multiple-choice concept exam. In answer to the second research question (i.e., What effect does the use of the conceptually based writing exercises have on students’ ability to justify their responses when answering conceptual questions related to basic electric circuit concepts?), the results

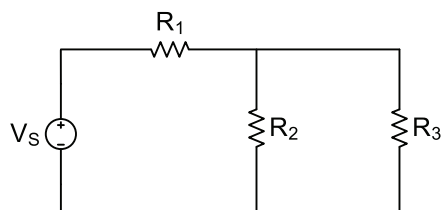
again suggest that the four additional writing quizzes did not appear to improve the quality of justifications for the not at-risk group; however, the quality of justifications was improved for the at-risk group.

While the results are preliminary, additional study of using such writing exercises appear warranted, particularly if feedback on the exercises is made both immediate and individualized. For this to be realized at scale, leveraging emerging techniques in NLP will be necessary. Indeed, through the use of standard NLP techniques, promising results of automatically identifying common misconceptions of students in one of the writing exercises has been demonstrated elsewhere [30]. Finally, as common misconceptions plague students in many gateway STEM courses and since writing has been shown to be effective in identifying and correcting misconceptions, interventions such as that described in this article could apply across common STEM courses.

## APPENDIX

All writing quizzes used in the study were administered in the paper format and followed the form of the quiz shown below.

Consider the circuit shown below and assume that the elements are ideal. Explain what happens to the power associated with  $V_S$ ,  $R_1$ ,  $R_2$ , and  $R_3$  as the resistance of  $R_2$  decreases while the other component values ( $V_S$ ,  $R_1$ , and  $R_3$ ) remain unchanged. Thoroughly *explain* the rationale supporting your conclusions, using equations only as necessary.



- 1) Rate your perceived understanding of the question in which a rating of 100% means you completely understand the question.
- 2) Rate your perceived ability to correctly answer the question by circling the appropriate response.
  - a) I am completely confident.
  - b) I am quite confident.
  - c) I am somewhat confident.
  - d) I have little confidence.
  - e) I am not at all confident.
- 3) OK, now complete the problem. Remember to write in full sentences and use as few equations as possible.
- 4) Now that you have answered the question, rate your perceived understanding of the question in which a rating of 100% means you completely understood the question.
- 5) Now that you have answered the question, rate your perceived ability to correctly answer the question by circling the appropriate response.
  - a) I am completely confident.
  - b) I am quite confident.
  - c) I am somewhat confident.

- d) I have little confidence.
- e) I am not at all confident.

- 6) Read through your response. Identify the sentence from your response with which you have the *least* confidence and explain why you question its accuracy.
- 7) Read through your response. Identify the sentence from your response with which you have the *most* confidence and explain why you are convinced of its accuracy.

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