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Identifying At-Risk Students in a Basic Electric Circuits Course Using Instruments to Probe Students' Conceptual Understanding

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Abstract

Electric circuit analysis is a gateway course for students in the electrical and computer engineering disciplines. Such courses build upon a foundation developed in the first weeks of class, making student success heavily dependent upon a strong command of this initial material. Therefore, it is paramount to identify struggling students early. This has prompted the search for instruments that can reliably identify at-risk students within the first week of class, as it is believed that this will afford sufficient time to provide the necessary assistance for at-risk students to succeed. For the purposes of this research, at-risk students are those identified as likely to receive a D, F, or to withdraw from the course.

This paper examines the use of various tools to help identify at-risk students in an introductory course in circuit analysis. Based on initial analysis, it is speculated that early activities that promote basic metacognitive skill development and the construction of proper mental models are critical to promoting success in the typical circuit analysis course. The features described provide a model for delivering meaningful assistance to at-risk students in such courses.

Introduction

Within many collegiate engineering programs, there are well-known gateway courses in which the DFW rates are in excess of 30% [1]. While numerous arguments exist as to why students struggle in these gateway courses, many of the purported reasons are related to either a general lack of appropriate study skills or to the nature of the content itself. Supplemental instruction has been thoroughly explored as a means to guide students toward developing general study skills and habits, as it has been asserted that "students who performed well in high school classes while exerting minimal effort, may not possess the necessary study skills appropriate for a rigorous college environment" [2]. Indeed, while students often believe their primary need is content-related knowledge, it is often the "prerequisite learning and thinking skills that are basic to content mastery" [3] which a student lacks. The notions of metacognition and self-regulation of learning are thus particularly relevant.

At its most basic level, metacognition can be understood as, "knowledge and cognition about cognitive phenomena" [4], but more specifically, metacognition may be defined in terms of information processing activities. For example, metacognition has been described as "the active monitoring and consequent regulation and orchestration of these processes in relation to the cognitive objects or data on which they bear" [5]. The self-regulated learner is one who employs metacognition – such an ideal learner, "would self-regulate their learning by identifying their own knowledge deficits, detecting contradictions, asking good questions that rectify these anomalies, searching knowledge sources for answers, making inferences when answers are not directly available, and actively building knowledge at deep levels of mastery" [6]. Supplemental instruction is certainly one way to help students cultivate general study and metacognitive skills, but resources (both time and money) and scalability need to be considered when designing supplemental instruction.

In addition to lacking pre-requisite study and metacognitive skills, students taking a gateway course such as introductory circuit analysis may be disadvantaged by entering the class with faulty mental models of basic concepts related to the subject. While circuit analysis may be first studied in earnest at the freshmen or sophomore level in college within an electrical and computer engineering degree program, concepts related to electricity and magnetism are often introduced into the curriculum much earlier. For example, many fourth-grade students in the United States have a module devoted to electricity and magnetism; in addition, students learn more about related phenomena in their high school and college physics courses. Faulty mental models and common misconceptions relating to the behavior of electric circuits have been documented elsewhere [7]-[13] and include, for example, belief that a battery is a source of a constant current, that current is consumed within a circuit, and that charge flow is a sequential process, for example. Flipping the classroom [14], addressing common misconceptions using appropriate modeling [15], and project-based learning [16] are examples of efforts to improve student outcomes in basic circuit analysis courses. Regardless of the reasons why certain students struggle in a gateway course, promptly identifying at-risk students and providing low-overhead interventions are critically important to improve retention within STEM disciplines at a time when growing enrollment in such courses limit instructional resources as is currently the case in the specific course under consideration.

This paper describes a search for instruments that can be used to identify at-risk students in an introductory course on electric circuit analysis and suggests an intervention to improve student success within such a course through both the formation of proper mental models of basic circuit phenomena and through the promotion of metacognitive skill in problem solving. Such an intervention should complement those proposed elsewhere that leverage a web-based instructional system currently under development [17].

Identifying At-Risk Students in an Introductory Circuit Analysis Course

The course considered in this work, EELE 201 – Circuits I at Montana State University, is a required four-credit course with a lab. The pre-requisites of this course are EELE 101, Introduction to Electrical Engineering Fundamentals and Calculus II. The emphasis of the pre-requisite electrical engineering fundamentals course is on providing students an overview of the fields of electrical and computer engineering; in addition, students are briefly introduced to Ohm's law, KCL and KVL as well as to introductory programming concepts. Approximately three 50-minute lecture sections are devoted to basic electrical concepts in the course. The introductory circuits course at Montana State University covers basic circuit quantities, Ohm's law, KCL, KVL, nodal and mesh analysis, circuit theorems, ideal operational amplifier circuits, the complete response of first-order circuits, sinusoidal steady-state analysis, and AC power, culminating in an introduction to ideal transformers. The follow-on circuits course covers second-order circuits, frequency response, Laplace transform techniques, the Fourier series, and basic filter circuits.

Over the span of the seven offerings of the introductory circuits course prior to the fall of 2014, the performance of students failing the course was studied. It was found that less than 5% of students who scored below 60% on exam 1 ultimately passed the course [17]. It was clear, therefore, that understanding what predicts a student's performance on exam 1 would facilitate identifying at-risk students, which in turn would be critical to marshalling and deploying available resources in the most effective manner. During the fall of 2014 semester, correlation analyses were performed between exam 1 scores and the following items: grades in a pre-requisite math course, scores on an in-class quiz that required use of a conceptual understanding of the derivative and integral in solving circuits-related topics covered in the first days of class, a modeling exercise within the second lab emphasizing conceptual understanding of a digital multimeter's impact on a circuit, the Motivated Strategies for Learning Questionnaire (MSLQ), and the DIRECT 1.0 (Determining and Interpreting Resistive Electric Circuits Concepts Test) [7] – a twenty-nine question, multiple-choice test developed for assessing students' conceptual understanding of DC circuits and uncovering their misconceptions. All reported correlations in this paper pertain to students taking EELE 201 for the first time.

While a strong correlation (Pearson's correlation = 0.64, n = 42) was found between Calculus II grades and exam 1 in EELE 201, Calculus II was not ultimately selected as a predictor as an increasing number of students are transfer students having completed Calculus I and II elsewhere and due to significant changes that have been made to the calculus sequence at Montana State University since fall 2014. The in-class quiz that involved use of the derivative and integral was an attempt to examine how students utilized their previous understanding of concepts from calculus in a new context, a transfer of knowledge problem. Moderate to weak (Pearson's correlation = 0.31, n = 42) correlation was found between the exam 1 score and the in-class "transfer quiz." It should be noted that exam 1 in EELE 201 contains little if any content related to calculus and thus any correlation between exam 1 and either calculus grades or the transfer problem quiz would speak more to a student's general ability to handle abstract concepts rather than to their ability to demonstrate a particular math skill. Certainly, students are required to demonstrate an understanding of basic calculus and the ability to manipulate complex numbers later in the course.

The laboratory activity required students to explain through words, sketches and simple calculation why a proposed measurement of current would yield a perhaps unexpected result. This laboratory modeling exercise score was found to exhibit weak to moderate correlation (Pearson's correlation = 0.32, n = 42) with a student's exam 1 score. It is speculated that the manner in which the modeling exercise was administered is a potential explanation for the lack of strong correlation with exam 1 performance. Unlike the other measures, the modeling exercise was completed with a lab partner and assistance was available from the lab instructor. It is reasoned that the weakness of an individual on the modeling exercise could be hidden through help available both from his/her lab partner and the lab instructor. As lab meets but once a week and getting students started properly in using the test equipment and in interpreting results is critically important, providing assistance in the early lab sections seems prudent.

Just days prior to exam 1 in the fall 2014 semester, both the MSLQ and the DIRECT 1.0 exam were administered. The MSLQ is "a self-report instrument designed to assess college students' motivational orientations and their use of different learning strategies for a college course" [18]. The MSLQ consists of two sections: one deals with student motivation, probing student goals and value beliefs for the course, as well as their beliefs about their ability to succeed in the course and their anxiety about tests in the course; the second section considers the learning strategies and resource management that a student believes he/she uses in taking the course. The

81 questions of the MSLQ were scored and assembled into fifteen groups as per [19], and included among other groups: intrinsic goal orientation, extrinsic goal orientation, task value, control of learning beliefs, self-efficacy for learning and performance, test anxiety, rehearsal, organization, critical thinking, time and study environment management, and peer learning for example. Only the self-efficacy for learning (Pearson correlation = 0.31, n = 42) and time and study environment management (Pearson correlation = 0.37, n = 42) rose to the marginal correlation level with exam 1. The MSLQ was not selected as a tool for identifying at-risk students on two accounts. First of all, for lack of a strong correlation between the MSLQ and exam 1, it does not seem reasonable to use the MSLQ in such a manner. Secondly, the creators of the MSLQ "assume that students' responses to the questions might vary as a function of different courses, so that the same individual might report different levels of motivation or strategy use depending on the course" [18]. Therefore, including the MSLQ to identify at-risk students within the first week or two of a course would not be appropriate as students would not have had the chance to develop a sufficient sense of the circuits course.

While a strong correlation between the various categories of the MSLQ and exam 1 in EELE 201 were not found, a Pearson correlation of 0.60 was found between the DIRECT 1.0 exam administered days before exam 1 and a student's exam 1 score. The fact that the DIRECT 1.0 is a simple multiple-choice exam and thus is easy to grade, and covers concepts meaningful from day one in a course on circuit analysis, it was decided that the DIRECT 1.0 exam would be further evaluated as a potential identifier of at-risk students. The most salient issue perhaps then is what score on the DIRECT 1.0 suggests a student is at-risk to fail the course.

It was found that in fall 2014, the semester in which the DIRECT 1.0 was administered in close proximity to exam 1, the lowest DIRECT 1.0 score to coincide with passing score on exam 1 was 19. It should be noted that scoring above 19 on the DIRECT 1.0 did not guarantee a student would pass exam 1. Using a score of 19 as the borderline case to differentiate at-risk students is questionable, however, as it is highly likely that this would significantly over-estimate the risk. Consider the box plots of the DIRECT 1.0 scores for the four semesters in which it has been administered as shown in Figure 1.

What is immediately noticeable when comparing the box plots of Figure 1 is that the median score in fall 2014 is significantly higher than those in fall 2015, fall 2016 and fall 2017. This is to be expected as the DIRECT 1.0 exam was administered immediately prior to exam 1 (~ week five of the course) in fall 2014 whereas it was given on day one of class in the subsequent fall semesters and certainly the weeks between day one of class and exam one offer ample opportunity for students to correct some of their misconceptions. The box plots also suggest that the mean scores in semesters in which DIRECT 1.0 was administered day one are similar within the 95% confidence interval. In the three semesters in which the DIRECT 1.0 exam was administered on day one, the overall mean score was 53% (σ = 15.7%, n = 187), which is similar to that reported in [7] and [15].

As was mentioned, using a day-one DIRECT 1.0 score of 19 as a cutoff makes little sense. Indeed, over the three semesters in which the DIRECT 1.0 was administered on day one, only 5% of students scoring at or above 19 failed the course. If not 19, what score on the DIRECT 1.0 should be used to identify a student as at-risk?

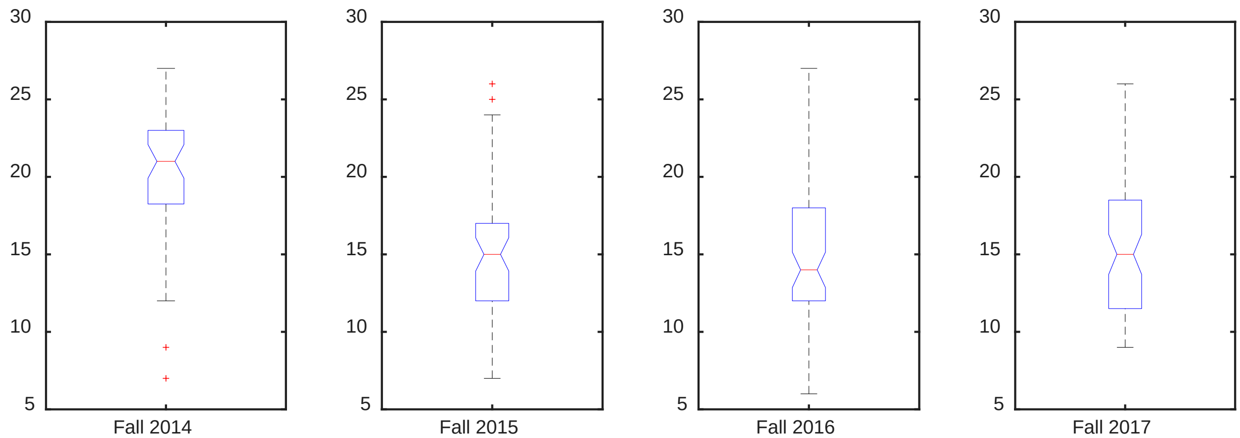


Figure 1: Box plots presenting DIRECT 1.0 scores across four semesters. The mean score is considerably higher in Fall 2014 as the DIRECT 1.0 exam was administered only days prior to exam 1 (~ 5 weeks into the semester) whereas in Fall 2015-2017, the DIRECT 1.0 was administered on day 1 of class.

It is tempting to speculate on which day-one score on the DIRECT 1.0 would translate into a score of 19 or greater by the time of exam 1. Since the DIRECT 1.0 was not administered a second time in the fall 2015-2017, it is not possible to compare progression in DIRECT 1.0 scores. Calculating the probability that a student with a given day one score has to fail the class is certainly possible, but the sample sizes of students with a given DIRECT 1.0 score are sufficiently small as to make the calculation of questionable utility. For example, over the three semesters in which the DIRECT 1.0 exam was given on the first day of class, there was only one student with a DIRECT 1.0 score of 6, only one student with a score of 7, but three students with a score of 8, and seven with a score of 9. Once above a DIRECT score of 9, the number of students with a given DIRECT score jumped to the double digits. As one possibility, scores of 14 and below on the DIRECT 1.0 could be chosen as defining the at-risk region. Such a range was arrived at by collecting the fall 2015-2017 DIRECT 1.0 scores into bins and considering the DFW rate for a given bin. Using the high-risk course DFW rate of 30% as a marker, students scoring at or below 14 had a 29.7% chance of failing the course.

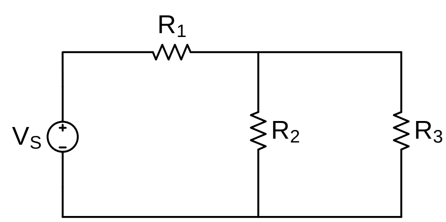
Clearly, there is no day-one score on the DIRECT 1.0 exam that can be used as a unique, definitive borderline identifying at-risk students. Furthermore, the format of instruction can have a significant effect on how readily students overcome common misconceptions [15]. Naturally, the lower the DIRECT 1.0 score, the larger the conceptual distance a student must make up by exam one. Certainly, some students scoring very low on the DIRECT 1.0 go on to excel in the course. What makes such students succeed? While the authors accept that the DIRECT 1.0 may be used to identify at-risk students in terms of their misconceptions regarding basic DC circuits, it is acknowledged that this is only one dimension of risk assessment for a course on electric circuit analysis. Other dimensions may include metacognitive and self-regulation of learning skills and simply engagement.

During the fall 2017 semester, an activity ultimately intended for use as an intervention to promote both formation of proper mental models and enhance metacognition in the course was introduced in a very limited form. As will be discussed shortly, this proposed intervention may be a more meaningful predictor of at-risk students in the course than those just considered.

Conceptual Understanding of Basic Circuits Through Writing Exercises

The question now is what interventions should be used to help at-risk students correct their misconceptions and enhance their metacognitive skill. As the desire is to maintain the DIRECT 1.0 as a purely diagnostic tool and not one for promoting learning, students did not receive feedback regarding their DIRECT 1.0 scores and no review of the questions or answers were given. During the fall 2017 offering of EELE 201, an in-class writing quiz in which emphasis is not only placed on the correctness of the response but also on how a student approaches the problem was introduced. The quiz given in the fall of 2017 is provided 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 as necessary.



It is your thought process that is the most important, so write what you are thinking and respond to all prompts given. You will have approximately fifteen minutes to complete the problem.

(1) Do you understand the question and do you think you will be able to meaningfully answer the question? (Even if you don't feel you understand the problem, please attempt to complete the exercise.)
(2) *How will you start this problem and what prior knowledge do you have to answer the question?*
(3) OK, now complete the problem.

The quiz was developed to both determine what misconceptions students exhibited in solving the problem and to probe students' metacognitive processes. The "warm up" questions, numbers 1 and 2, are meant to trigger metacognitive activity in the student by guiding them to consider whether they understand the problem and whether they can connect any prior knowledge to the problem. Taken together, these three prompts can be thought of as the first three phases of the solving mathematical problems process suggested by Polya [20]. Polya's fourth and final stage of "looking back" has the solver attempt to check his/her result or to try to solve the problem in a different manner. While this fourth phase was not a part of the quiz, it certainly could be included.

This quiz was administered on the fifth day of class in the fall of 2017 and students were told that as long as they gave a sincere effort, they would receive at least a score of 70%. The results from all quizzes suggested that all students gave forth a legitimate effort. Evaluation of the quizzes was accomplished using a holistic approach. As a first step, the quizzes were divided into three groups: a high-end group (score of five) in which the responders gave a complete or nearly complete and accurate response with suitable justification, the low-end performers (score of one) who gave little to no discussion, did not truly address the question, or whose responses were riddled with misconceptions and faulty logic; the middle group (temporary score of three) fell between these two extremes. It should be noted only question three was considered (the warm-up questions were ignored during initial grading) and that as long as the student presented a well-reasoned response, even if it happened to be based on a key misconception, the quiz would find its way into the middle group. The piles at this stage consisted of approximately 14% at the high end, 22% at the low end, and 64% in the middle.

The second stage involved a re-examination of the middle group in an attempt to separate them into three groups. The sorting of the middle group into better than average and poorer than average was done with an emphasis on richness of response and evidence of metacognitive activity. Clearly, there were some in this pile with largely accurate, though perhaps not as complete responses as those scoring a five; such quizzes were scored with a four. While those exhibiting a major misconception would not be moved above the middle to a score of four, as long as the argumentation was sound, though perhaps based on an incorrect starting point, such quizzes were placed in the middle (score of three) of the second sorting. Quizzes that ended up with a score of two were those that, while perhaps not exhibiting major misconceptions, lacked sufficient and clear discussion to warrant a score of three. In general, identifying scores of one, four and five was fairly straightforward, whereas separating groups two and three was more subjective. An example of the type of response that could end up with a score of three is one based on the premise that the circuit to the left of R_2 is unaffected by changes in R_2. Clearly, this is a serious misconception that must be corrected. If the student exhibiting this misconception went on to elaborate in detail, and in a logical fashion, what would happen with the power associated with the elements, the quiz would be scored a three. Again, the answers provided in such cases were erroneous because they were based on a faulty model, but the richness in the response could justify a score of three if the student demonstrated sound logic and clear metacognitive activity.

The rationale for grading the writing quiz in this manner is that by choosing such a grading scheme, additional insight into a student's mental processes and approach to conceptual problems was possible in a way in which the multiple choice DIRECT 1.0 does not allow. It was felt that students exhibiting such metacognitive skill are just the type to conquer their misconceptions given the opportunities as the course currently affords. Figure 2 shows a plot of the exam 1 scores versus the writing quiz scores using the holistic grading approach just described.

While the exam 1 and writing exercise scores appear to correlate, a logarithmic, rather than linear fit seems more appropriate. The mean, median, standard deviation, and 95% confidence interval of exam 1 scores for the five possible writing scores are given in Table 1 as are the number of occurances (n) of each writing score.

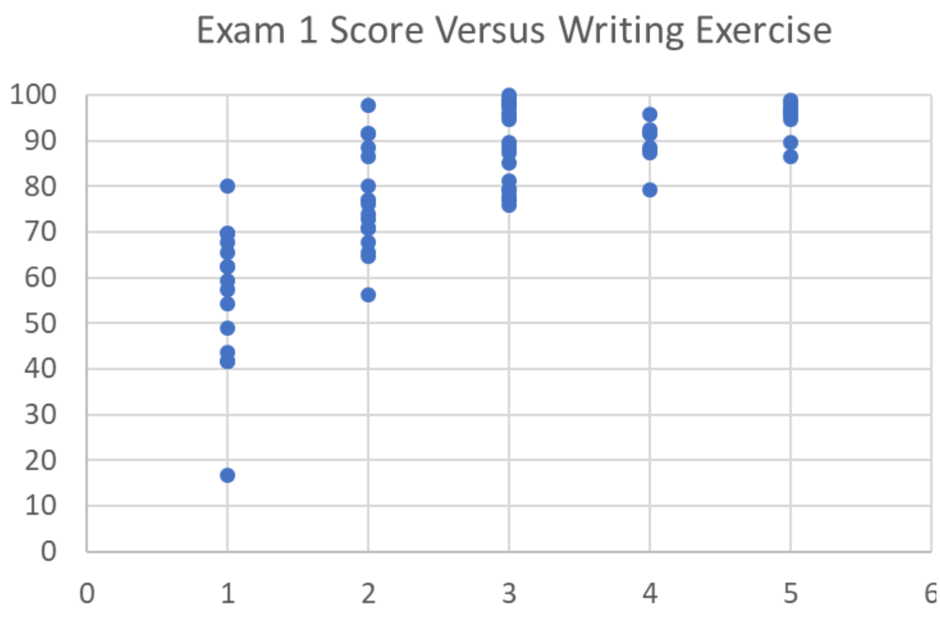


Figure 2: Exam 1 scores versus writing exercise scores; a higher score suggests better performance.

Table 1: Descriptive Statistics of Exam 1 Scores for Each Possible Writing Score

Writing Score	Exam 1 Mean	Exam 1 Median	Standard Deviation	95 % Confidence Level	n
1	56.11	59.38	15.71	8.70	15
2	77.77	76.56	10.78	5.88	16
3	89.82	92.08	8.72	4.08	20
4	89.34	90.10	4.97	4.15	8
5	95.00	96.35	3.92	2.81	10

We see from the data of table 1 that the mean and median exam 1 scores tend to increase with writing 1 scores, drammatically so at the lower end. The spread in the exam 1 scores decreases as the writing score increases. While any conclusions drawn from these data are certainly preliminary and considerable more study is necessary, several intriguing observations may be made. For example, it seems that little subsequent concern should be invested in students scoring a four or five on the writing quiz – their ultimate success seems assured. While the spread in exam 1 scores for those with a writing score of three is larger than those of groups four and five, little concern over students scoring a three on the writing quiz appears justified as well. As noted above, numerous students scoring a three on the writing exam exhibited a key misconception – what distinquishes students with a score of three is that such students seem far more likely to correct such misconceptions by exam 1. On the other hand, students scoring a one on the writing quiz could be deemed at risk – of the fifteen students scoring a one on the writing quiz, eight scored below 60% on exam 1 and fourteen score 70% or below. The vast majority of students scoring a two on the writing quiz performed reasonably well on exam 1, and some performed very well. As noted above, the original intent for this writing quiz was to determine how such an instrument correlated with exam 1 and then to use such quizzes as tools to combat misconceptions and improve metacognitive skill – it seems perhaps that this could be a powerful tool for identifying at-risk students.

To evaluate whether there were any differences in the five scored writing groups in terms of their answers to the two warm-up questions, each of the five bins was re-evaluated by focusing on student responses to these questions. The first warm-up question was scored as either a zero or a one. As long as the student responded as to whether they felt they understood and could meaningfully answer the score, they were given a one. All but five quizzes had responses for this question. Three of the five instances in which a student failed to answer question one came from the lowest bin. It is interesting to note that of the two highest scoring bins (four and five), only one student out of eigthteen expressed any doubt that they could answer the question meaningfully, whereas 20% of group three expressed some doubt, 69% of group two expressed some doubt, and 33% of group one expressed some doubt. The fact that the lowest scoring group expressed considerably less doubt regarding their ability to answer the question when compared to the next higher group, emphasizes that the lowest scoring students were largely innacurrate in their self-assessment and thus demonstrated poor knowledge of cognition [21].

The second question was scored either a zero, one, or two. If the student failed to answer question two or gave a very generic response such as “KVL” or “conservation of power” his/her question was scored a zero. Question two responses that included reference to series and parallel combinations of resistors, for example, scored a one, and responses with more detailed plans were scored a two. It was quite apparent that many students in the top two scoring bins had honed in on properly answering the question with the question two prompt. Taken together, scores on the two warm-up questions could range from zero to three. Table 2 provides the mean values, standard deviation, and 95% confidence interval as well as the number of samples (n) for each writing score bin.

Table 2: Descriptive Statistics of “Warm-Up” Scores for Each Possible Writing Score

Writing Score	**Warm-up questions Mean**	**Standard Deviation**	**95 % Confidence Level**	**n**
1	1.47	0.52	0.286	15
2	1.71	0.47	0.241	16
3	2.30	0.57	0.267	20
4	2.38	1.06	0.887	8
5	2.67	0.5	0.384	10

Due to the limited number of samples and the fact that the confidence intervals overlap in several cases, a high degree of certainty cannot be held in the results presented in Figure 2. The large spread in group 4 as portrayed in table 2, for example, is due to the fact that the single score of zero of the entire 69 students occurred in group 4 – the group with the smallest population.

While larger-scale testing is necessary to determine whether there are statistically significant differences between how the groups of students performed on the warm-up questions, the results do suggest the possibility that students scoring at a higher overall level on question three of the quiz – the actual problem itself, exhibited stronger command of the orientation and organization phases of problem solving [22]. The authors suggest a few possible changes to the writing quiz to better answer this question. First, as part of warm-up question one, it would be more meaningful to have students both rate their confidence to meaningfully answer the problem using a numeric scale and to demonstrate their understanding of the problem by succinctly putting the problem statement into their own words.

As it stands and with the suggested improvements, further study of the use of such writing quizzes not only as a tool to identify at-risk students, but more importantly as a means to help students overcome misconceptions and to enhance their metacognitive skill seems warranted. For instructors contemplating moving from a purely lecture-based format to one in which active learning methods are employed, such writing quizzes seem ideal as they can foster much post-quiz discussion among students. For example, an entire 50-minute class period could be taken up with just the writing quiz presented here. The first 15 minutes of class could have students complete the quiz individually. Once the quizzes are handed in, students might then group to discuss the problem again and develop a consensus solution. Again, the group solutions could be collected for grading. Finally, the instructor could bring back the attention to the entire class to discuss the problem collectively. Such a plan is that of one of the authors going forward. It is believed that the first part, in which each student attempts the problem not only via equations, but more importantly through written elaboration, is vital and that the instructor emphasize that a student's thought process is what will be given most weight in grading. Typically, there is great disparity in student preparation and ability upon arrival in EELE 201, and allowing each student time to digest and attempt the problem on his/her own is justified. There is evidence that cooperative learning combined with metacognitve training is effective in promoting mathematical reasoning and metacognitive knowledge [23] and so the second stage of having students group and discuss should likewise be important. It has been said that, "writing is applied metacognition" [24], and such an activity with appropriate feedback from classmates and the instructor should help to develop a student's metacognitive skill.

Conclusions

A number of instruments were investigated to help identify at-risk students in a course on basic electric circuit analysis. It is reasoned that identifying such students early in a course opens the possibility to devote available tutoring resources in the most effective manner and with sufficient time to significantly improve the student success rate in this gateway course to the electrical and computer engineering disciplines. Preliminary assessment on a limited scale suggests that a writing quiz probing a conceptual understanding of elementary circuits may be a very effective tool in this regard. Such problems not only elicit common student misconceptions, but also shed light on the level of metacognition and reasoning skills. It appears that as long as students exhibited an ability to follow a well-reasoned path of logic, even if based on common misconception, their chance to clear up their misconceptions in the weeks between the writing quiz and exam 1 were great. Students resorting only to an equation or two, or who showed little evidence of following a logical path to a conclusion were at great risk to fail the first exam, and subsequently the course. It must be stressed that these results are preliminary, based on a single writing exercise administered to approximately 70 first-time students in an introductory course on circuit analysis Efforts are underway to develop other such writing tools not only for identifying at-risk students, but more importantly as interventions to promote not only the formation of proper mental models of abstract concepts, but also to foster metacognition.

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