



The Use of SPICE Simulation to Promote Reflection and Metacognition in a Microelectronics Course

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Abstract

Several theories, including Experiential Learning Theory, describe the importance of reflection for learning, and a host of articles have called for additional research on reflection in engineering education. Ambrose has called for engineering curricula with “opportunities for reflection to connect thinking and doing,” since students learn by doing but only when they reflect on the doing too. Regular reflection plays a critical role in the construction of metacognitive knowledge and self-regulatory skills, which includes monitoring and evaluating one’s own learning, knowledge, and skills. Unfortunately, the development of metacognitive skills is often not formally included within curriculums. However, simple in-class active learning exercises, such as think-pair-share or minute papers, as well as post-exam analysis by students, can promote reflection and metacognition. In a microelectronics course, we recently incorporated post-exam reflective exercises using SPICE simulation tools to guide students’ reflections on errors made and strategies to improve future performance. The instructor was inspired to use this approach after learning of its use in an introductory circuits course. In the circuits course, the instructors had used a reflective approach known as Exam Analysis and Reflection (EAR), which had previously been developed for mechanical engineering courses.

In the microelectronics course, we preliminarily incorporated reflective exercises after two exams and applied the EAR with the second. After the first exam, students used the simulator to correct any errors, which introduced them to using simulation for reflection. With the second exam, which was a small quiz, a similar procedure was followed, in which students used the simulator to reconstruct the amplifier circuit on the exam. Thus, students used the simulator to “re-do” the quiz to determine the simulated values, with the goal of having students recognize and question any differences, which could have resulted from calculation errors or natural differences between simulation and hand calculations, among other reasons. Students were then asked to reflect on the following questions from the EAR approach: “How is my exam result different from the simulated result?“, “What went wrong with my solution?“, and “How can I use this to improve my performance in the future?”

To assess the impact of using simulation to reflect on their exams, we interviewed students as well as directly assessed their performance. Students were given a final exam problem that was very similar to the quiz problem where they applied the EAR approach. We compared the results from this final exam problem to those from the prior year (without reflection), in which the final exam was the same. We also determined the correlation between the quality of students’ reflections and their performance on this final exam problem. We assessed the quality and depth of the reflections using a four-category rubric from the published literature. The preliminary results have been promising, showing evidence of students’ appreciation of the reflective approach in their interviews and depth in their EAR responses. The interview data also highlighted lessons on improving our initial implementation of simulation for this type of reflection and comparison.

1. Introduction and Relevant Literature

We recently developed a classroom-based, simulation-centric approach to instruction in an undergraduate microelectronics course. In this approach, SPICE simulation tools were frequently used for lectures, post-exam reflection, and in-class activities involving pair simulation, a variant of the pair-programming technique. The instructor implemented this new approach given his inclination towards active learning and his belief that this was a novel as well as potentially beneficial approach for active-learning-based instruction in microelectronics. The instructor's perception of the limited use of simulation in the electrical and computer engineering classroom for active learning was indeed confirmed by a search of the literature. Our hypothesis was that simulation would enable students to develop deeper insights into complex microelectronic circuits - beyond those possible through commonly-taught equations. With introductory microelectronics, students must transition from analyzing circuits with simple linear elements (such as resistors, capacitors and inductors) to circuits with complex, non-linear components (such as diodes, transistors, or logic gates), which depend on a large number of parameters and exhibit different behaviors over a range of operating conditions. The preliminary results of this use of simulation in the classroom have been highly positive based on both direct and indirect student assessments (Dickerson & Clark, 2018).

As mentioned, we incorporated post-exam reflective exercises using SPICE to guide students' reflections on errors made and strategies to improve future performance. Others have advocated or used post-exam reflections to drive metacognitive skills development, including via the EAR approach (Exam Analysis and Reflection) used in this study (Steiner & Foote, 2017; Claussen & Dave, 2017; Benson & Zhu, 2015). Interestingly, the literature has indicated a need for additional scholarly research on reflection in engineering education, with limited publications to date (Turns et al., 2014). Turns and Atman recently began work in the fall 2017 semester on an NSF-funded study on reflection, stating in their abstract that "...within engineering education, reflection and reflection activities are *understudied*." (Turns & Atman, NSF Award No. 1733474).

Reflection is important because, based on Kolb's Experiential Learning Model, learning occurs through a combination of *doing* as well as *reflecting on the doing*. Schon's theory of the reflective practitioner maintains that reflection is key to professional practice, including the "back-talk" that occurs between the reflective designer and the situation that may assist in a deeper understanding of the problem (Adams et al., 2003). Likewise, Ambrose has called for engineering curricula with "opportunities for reflection to connect thinking and doing," and the "development of students' metacognitive abilities to foster self-directed, lifelong learning skills." (Ambrose, 2013, p. 16-17). Ambrose highlights a gap in the formal inclusion of metacognitive activity in the engineering curriculum (Ambrose, 2013). Regular reflection plays a critical role in the construction of metacognitive knowledge and self-regulatory skills – or planning for, monitoring, and evaluating one's own learning, knowledge, and skills (Schraw, 1998; Steiner & Foote, 2017). Metacognition is "knowing about knowing," and a metacognitive student is one who is aware of his/her learning process and can adjust this process as needed (Turns et al., 2014; Steiner & Foote, 2017).

2. Methods

Classroom Methods

In our simulation-based microelectronics course in the summer 2017, we incorporated reflective exercises after two exams, applying the Exam Analysis and Reflection (EAR) approach with the second exam. The instructor was inspired to use the EAR approach after learning of its use in an introductory circuits course after it had been developed for mechanical engineering courses. After the first exam, students used the simulator to correct any errors, which introduced them to using simulation for reflection. With the second exam, which was a quiz with multiple sequenced questions, a similar procedure was followed. The instructor returned the graded quiz to the students without the answers. Students then used the simulator during class to reconstruct the amplifier circuit on the quiz and “re-do” the quiz to determine the associated simulated values. Figure 1 illustrates our approach. One of the primary goals was for students to reflect on (i.e., recognize and question) any differences, which could have resulted from calculation errors on the quiz or expected differences between simulation and hand calculations, among other reasons. Another goal was for the students to use the simulator to correct their responses, identify where their solutions went wrong, and hopefully understand the problem at a deeper level. With the simulator, the students would be able to see the impact of a change in a single variable or component on the overall amplification system output. The instructor encountered no additional burden (beyond what is typical with any assignment) in implementing this method, other than ensuring that students knew how to use the simulator for reflection.

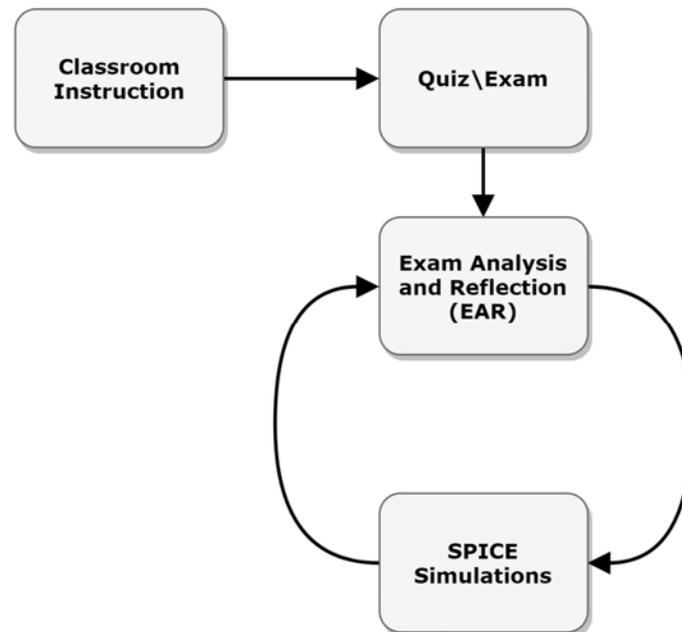


Figure 1. Illustration of classroom instructional methods. After an exam, the Exam Analysis and Reflection approach is used in conjunction with SPICE simulation.

Description of Quiz

For the quiz, students were asked to realize an amplifier with a specified gain (Figure 2), using a MOSFET in a common-gate configuration (Figure 3). This circuit problem was used to assess the effectiveness of our instructional method because it requires students to complete multiple

steps to obtain a correct answer. Specifically, students had to demonstrate an ability to carry out a DC analysis of the circuit, use the result to determine small-signal parameters, derive an AC equivalent circuit model, determine the amplifier gain by analyzing the equivalent circuit, and verify that the solution did not violate the assumption that the MOSFET always remains in the saturation region of operation. Correctly performing all these analyses and calculations required mastery of several mathematical techniques, a solid understanding of a variety of concepts, and knowledge of how those concepts related to one another. The challenge for students was that an error during any one of the steps resulted in an incorrect solution, with the source of error very difficult for them to trace. Figure 4 shows an example simulation result. With the use of a SPICE simulation environment, students could quickly verify whether or not their hand-calculated parameters resulted in a correct solution. In the case that it didn't, students could perform a rapid design-space exploration to potentially reveal where they made mistakes.

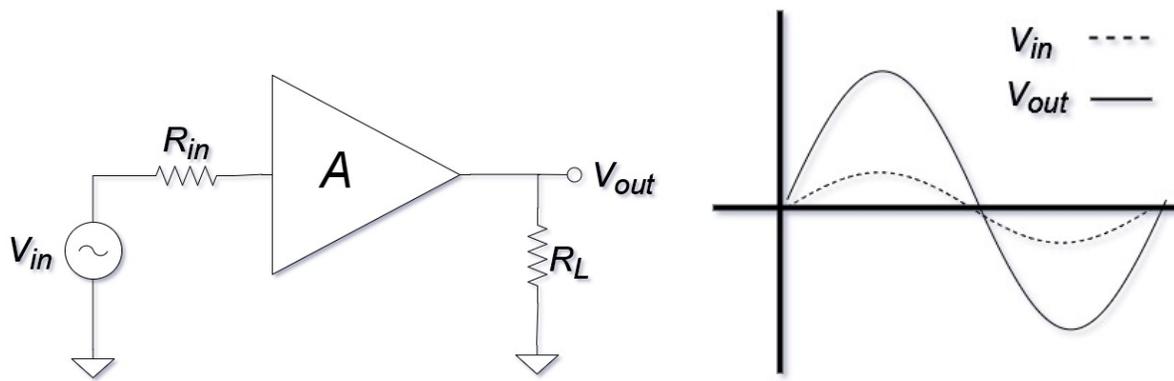


Figure 2. Depiction of quiz: design of an amplifier that meets a certain gain requirement.

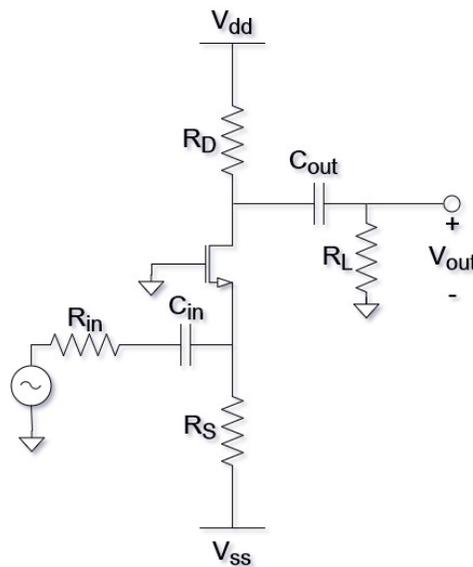


Figure 3 Specified amplifier topology (MOSFET common-gate). Solution requires knowledge of linear and non-linear circuit elements as well as DC and AC circuit analysis techniques.

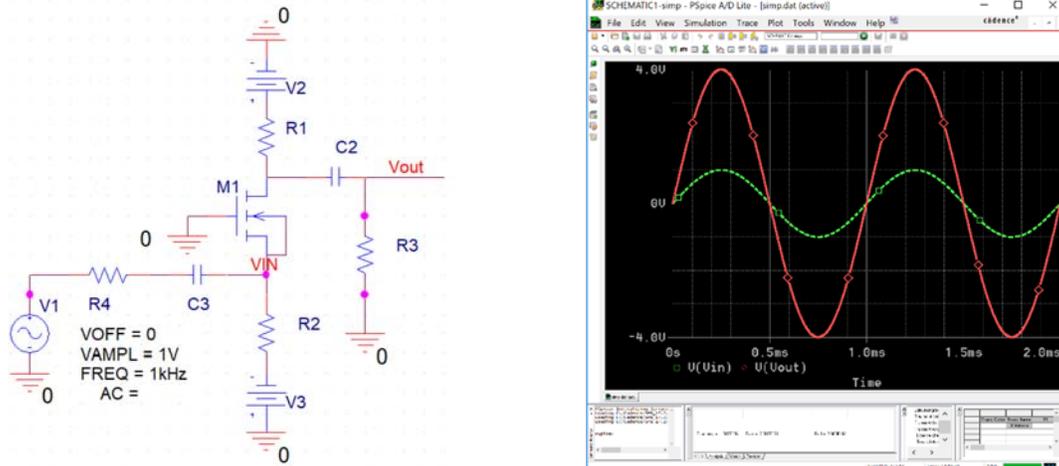


Figure 4 Example schematic and results from the SPICE simulation environment.

Student Reflective Activity

Students were asked to reflect on five quiz questions, which pertained to the calculation of the following circuit values: 1) MOSFET overdrive voltage (V_{ov}), 2) Source voltage (V_s), 3) Source resistance (R_s), 4) Voltage gain (A), and 5) Drain resistance (R_D). The quiz questions were an ordered series of problems that culminated in calculating a targeted value. We analyzed the depth of the reflection associated with each of the five quiz problems separately, since each problem required distinct skills. For each problem, students were specifically asked to reflect using the EAR approach as follows: 1) How is my exam result different from the simulated result?, 2) What went wrong with my solution?, and 3) How can I use this to improve my performance in the future?

Assessment of Reflections

The depth of the reflections was assessed using a four-category rubric from the literature that ranged from level 1 (non-reflection) to level 4 (critical reflection) (Kember et al., 2008). The instructor and assessment analyst independently assessed the depth of each reflection and then discussed any discrepant ratings to reach consensus. Thus, although all reflections were coded by two analysts, the first-time inter-rater reliability based on all quiz questions was calculated. ICC (intra-class correlation coefficient) values of 0.89 (average measures) and 0.79 (single measures) were achieved, each suggesting strong/excellent agreement beyond chance (Norusis, 2005; Fleiss, 1986; Lexell & Downham, 2005; Hallgren, 2012).

In addition to assessing depth, they also independently conducted a content analysis of each reflection. The coding scheme for this (shown in Table 1) was developed by the assessment analyst via an emergent qualitative analysis of all student reflections prior to coding them (Neuendorf, 2002). As with the depth rating, the assessment analyst and instructor independently assessed the content of each reflection and then discussed the discrepant codes to reach consensus on final content codes. In the content analysis, a reflection could have more than one content code associated with it. Although all reflections were coded by both analysts for content, the first-time inter-rater reliability (based on all quiz questions) was calculated and found to be Cohen's kappa $\kappa = 0.67$, suggesting fair to good agreement beyond chance (Norusis, 2005).

Table 1: Coding Scheme: Reflection Content Areas

Actions	Code
1. Iteration is/was required; Items were re-worked; Check or double check; Be more careful; Revisit if unsure; Ensure results make sense; Do upstream verification; Errors cascade; Consider the whole problem	ITER
2. I can or should ask others	ASK
3. I need more practice or review of certain topics; I was not knowledgeable of or was confused about certain topics; I need to know more in the future; I need to improve; Did I recall things correctly?	REVIEW
4. Don't incorrectly assume; Assumptions have consequences; Was I wrong to assume?	ASSUME
Questions	
5. How large of a difference is too large or unacceptable?	LARGE
Realizations	
6. Simulation is more thorough, accurate, or realistic than hand calculations; There are differences between simulated and hand-calculated values	SIM

Assessment of Reflections vs. Exam Performance

We investigated student performance in relation to their reflection in several ways. First, we determined the correlation between the depth of students' reflections and their performance on several of the final exam problems that were similar to the quiz questions on which they reflected. This was done to assess the relationship between the quality of reflection and subsequent analytic performance. The correlation was measured using the non-parametric Spearman's rho given the ordinal nature of the data (McDonald, 2014). In addition, we compared the results of these particular final exam problems from the summer 2017 (with reflection) to those from the prior summer (without reflection). For both semesters, the final exam was exactly the same, and the instructor graded all exams at the same time (using a rubric) after shuffling them to obscure the particular semester. An analysis of covariance (ANCOVA) was used to compare the exam results, with the pre-course GPA used as the covariate, or control variable, in order to take prior academic performance into account. Since the sample size was small ($n=22$) for the semester with the reflection, we also ran the non-parametric version of ANCOVA, known as Quade's test (Quade, 1967; Lawson, 1983). The p -values based on the parametric and non-parametric analyses were in general agreement, and examining both served to corroborate the results. However, we defaulted to the non-parametric result given the smaller sample size. In addition, Cohen's d effect size was calculated to determine the practical significance of the difference, with values of d below 0.50 considered small and values of 0.80 or above considered large (Cohen, 1988; Sullivan & Feinn, 2012). Given the small samples, Hedge's g effect size was also calculated, although these results were in close agreement (Lakens, 2013).

Student Interviews

Finally, to assess the perspectives of the students about using simulation to reflect, we individually interviewed 68% of the students using the question shown in Table 2. We also used this interview data to detail ways to improve our initial implementation of simulation for this type of reflection and comparison.

Table 2: Interview Question

<i>What was the impact of using the simulation software after the test to review and analyze your test responses?</i>

3. Results

We analyzed reflections from 23 students who took the course in the summer 2017 semester for both depth and content. The results are discussed below by quiz question, with side-by-side results of content and depth presented afterwards in Table 3.

Quiz Problem 1 – Overdrive Voltage (V_{ov})

This question was the first one on the quiz that entailed a comparison of hand calculations to simulated values, where students could see firsthand a difference between them. (Recall that the quiz questions were a sequential buildup to a target calculation.) Not unexpectedly, the most frequent reflective content area for this quiz problem was the realization that simulation is more thorough, accurate, or realistic than hand calculations (SIM), as indicated by 43% of the students.

Quiz Problem 2 – Source Voltage (V_s)

This question involved choosing the correct equation and applying it using the correct parameter values. The most frequent content area for this problem was also SIM, or the realization that simulation is more accurate, as identified by 39% of the students.

Quiz Problem 3 – Source Resistance (R_s)

The reflective depth associated with this problem was the lowest among the five quiz problems - at an average value of 1.61 on the four-point scale. Not surprisingly, the occurrence of various content areas was also lower than for the other quiz problems. ITERATION was the most frequently occurring content area, as students witnessed first-hand the propagation of their errors from problem 2 and hence the need to check their results to a greater degree. The reflection required to understand and articulate their performance on problem 2 may have affected the reflective depth provided for problem 3.

Quiz Problem 4 – Voltage Gain (A)

This problem involved calculating the voltage gain and was the most challenging question on the quiz. It relied on a solid understanding of concepts, as opposed to simply choosing the correct equation. Interestingly, the most-frequently stated content area for this problem was REVIEW, or the acknowledgment that more practice or review of certain topics was needed to improve the student's knowledge or understanding. This acknowledgement was made by 57% of the students. Thus, in a positive fashion, this quiz problem led students to reflect on their performance and conclude that there were gaps in their knowledge or understanding. This quiz problem was associated with reflections of the greatest depth, with an average depth of 2.30 on a 4-point scale.

Quiz Problem 5 – Drain Resistance (R_D)

This question, like question #2, entailed applying the correct equation. However, keeping in mind this problem was downstream in the solution process, the most-frequently mentioned reflective content area for this problem was ITER, or the acknowledgement that upstream

verification and careful checking is important, as errors do cascade, often leading to re-work. This was identified by 57% of the students. This quiz problem was associated with reflections of the second-greatest depth, with an average depth of 2.22 on a 4-point scale.

A side-by-side comparison of the reflective content areas and depth associated with each quiz problem is provided in Table 3. The average reflective depth associated with each quiz problem is presented at the bottom of the table. As shown in Table 3, the content areas SIM, ITER, and REVIEW were frequently the subject of the reflections, depending on the particular quiz problem. The reflective content areas ASSUME, LARGE, and ASK occurred relatively less frequently.

Table 3: Content & Depth Results by Quiz Problem

<i>P1</i> <i>Vov</i>		<i>P2</i> <i>Vs</i>		<i>P3</i> <i>Rs</i>		<i>P4</i> <i>Av</i>		<i>P5</i> <i>Rd</i>	
Content	% Students	Content	% Students	Content	% Students	Content	% Students	Content	% Students
SIM	43%	SIM	39%	ITER	26%	REVIEW	57%	ITER	57%
ITER	22%	ITER	17%	SIM	17%	ITER	26%	REVIEW	39%
ASSUME	9%	REVIEW	9%	REVIEW	9%	ASSUME	13%	SIM	4%
LARGE	4%	LARGE	4%			SIM	9%		
REVIEW	4%								
ASK	4%								
Depth	% Students	Depth	% Students	Depth	% Students	Depth	% Students	Depth	% Students
1	39%	1	35%	1	57%	1	17%	1	17%
2	30%	2	43%	2	26%	2	35%	2	43%
3	30%	3	22%	3	17%	3	48%	3	39%
4	0%	4	0%	4	0%	4	0%	4	0%
Average Reflective Depth (Scale: 1-4)									
1.91		1.87		1.61		2.30		2.22	

Note: depth was assessed on a 1-4 scale, with 4 indicating the greatest depth (i.e., critical reflection).

Analysis of Reflection: Final Exam Results

Two final exam problems were very similar to the quiz problem where students applied the reflective approach. These final exam problems were 1.2 on AC analysis and problem 2 on small signal analysis. In comparing the results of these problems from the reflective versus non-reflective semesters, the reflective semester had the higher scores, as shown in Table 4.

Although the parametric ANCOVA results were statistically significant, the non-parametric ANCOVA results were not. Given the smaller sample size associated with the reflective semester, we defaulted to the non-parametric results and concluded non-statistically-significant results for this preliminary analysis. However, the effect sizes were medium, with Hedge's $g=0.63$ for problem 1.2 and $g=0.55$ for problem 2, suggesting preliminary evidence of practical significance of the higher scores from the reflective semester. The Cohen's d values were in very close agreement to the Hedge's g values.

Table 4: Final Exam Comparison

Exam Problem (/10)	Adjusted Mean Score		p-value		Effect Size	
	Reflection (n=22)	Non-Reflective (n=31)	ANCOVA (parametric)	Quade's Test (non-parametric)	Cohen's <i>d</i>	Hedge's <i>g</i>
1.2 - AC Analysis	8.10	6.99	0.028	0.097	0.64	0.63
2 - Small Signal Analysis	8.37	6.96	0.051	0.118	0.56	0.55

We also measured the relationship between the quality (i.e., depth) of students' reflections and their performance on final exam problems 1.2 and 2. A correlation analysis of reflective depth versus achievement on each of these problems did *not* uncover a significant relationship at this time. For the correlation of exam problem 1.2 (AC analysis) with the reflective depth associated with quiz problem 4 (Av), Spearman's rho was 0.068, a small correlation that was not significantly different from zero. The correlation of exam problem 2 (small signal analysis) with the reflective depth associated with quiz problem 4 was actually negative, with Spearman's rho = -0.191, which was also not significantly different from zero. Together, these correlations suggest an uncertain relationship at this time (i.e., based on the data we currently have) between the depth of reflection on a problem and analytic performance on a subsequent related problem.

Student Interview Results

The interview results showed evidence of students' appreciation of the reflective approach. We interviewed 15 of the 23 students in the course, asking them about the impact of using the simulation after the test to review their test responses. A sample of student responses reflecting this appreciation are shown in Table 5 and discuss the themes of iteration, retention of information, differences between simulation and hand calculations, asking questions, the simulator as a means of verifying answers, and review of performance and course content. Interestingly, the interview themes were in line with and similar to the categories in the coding scheme in Table 1, serving to triangulate the data.

Table 5: Interview Responses Exhibiting Appreciation of Reflection

I learn best by trying, failing, and then trying and failing again. It helps me. With this method, I got the chance to try the quiz again. Going back is part of the process of learning for me.
It impacted my memory to last longer; this was impressive. I remembered my quiz/test mistakes. Also, the results I got on paper were different from reality, but I was not surprised. It drove me to ask Dr. D questions as to why there was such a difference, because I wondered why it was the case. I learned I was not necessarily correct, as I had originally thought. I had to question my correctness with Dr. D.
I know how to check using resources at my disposal (i.e., simulation software) to confirm the answer.
It helped to look at problems I had with the quiz, in order to review better or look more in the book. It gave me a chance to explore the answers on my own and learn from my mistakes.

The interview data also highlighted lessons on improving our initial implementation of simulation for this type of reflection and comparison. One of the primary lessons learned was the need to better instruct students on *how* exactly to use the simulator to reflect on their answers.

4. Discussion & Conclusions

We recently developed a simulation-based approach to classroom instruction in an undergraduate microelectronics course, where SPICE simulation tools were used for post-exam reflection as well as in-class active learning. Experiential Learning Theory describes the importance of reflection for learning, and a host of articles have called for additional research on reflection in engineering education. Our article is a response to this recent call. In this paper, we analyzed the depth and content of post-quiz reflections, which students completed using the SPICE simulator. On a four-point scale, the average depth of the reflections associated with the various quiz questions ranged from 1.6 to 2.3, with 4 being the maximum possible. In addition, the content areas SIM, ITER, and REVIEW were frequently the subject of the reflections, with the content areas ASSUME, LARGE, and ASK occurring relatively less frequently. The variation in reflective levels and content areas across the quiz questions provides insight into the types of problems that may elicit reflections of different depths and content, which can be used to design future problems. We did not assess any of the reflections to be at a depth of 4, which would have indicated critical reflection.

A future research goal is to prompt students to reflect critically (at a level of 4), either by enhancing their reflective practices, providing the “right” types of microelectronics problems to reflect on, or a combination of both. To be a critical reflection, there must be evidence of a change in perspective over a fundamental belief. Undergraduates often form deep-seated beliefs, including continuing to interpret phenomena in terms of less sophisticated theories, despite having been taught more sophisticated models at a later time (Kember et al., 2008). We encounter examples of this in practice and plan to work with eliciting critical reflection in this area. The long-term goal of our research is to comprehensively understand the role of simulation and associated reflection in the professional formation of engineers with respect to open-ended problem solving and design.

In addition, in preliminarily comparing the results of particular final exam problems from the reflective and non-reflective semesters, the reflective semester was associated with higher scores, although not significantly so at this point. These exam problems were very similar to the quiz problem in which the students had applied the reflective approach earlier. Nonetheless, the effect sizes for the differences were medium, providing some preliminary evidence of practical significance of the higher scores during the reflective semester.

In this paper, our approach involved an introductory electronics course with SPICE simulation, but our methods are broadly applicable to many other topics in electrical and computer engineering. For example, within most computer engineering curricula, students complete courses in digital hardware and are asked to design and simulate complex digital systems. In that context, our methods could easily be adapted to make use of HDL simulators (e.g., Mentor's Modelsim) to promote reflection. An additional opportunity for use of these methods in ECE curricula is in advanced signal processing courses that are common to all electrical engineering programs. The material associated with these courses is highly theoretical and instructors are confronted with many of the same educational hurdles as in a microelectronics course. Such math-intensive courses would benefit greatly by incorporating many of the widely available model-based simulation tools (e.g., Matlab's Simulink) that can be used to simulate continuous-

time and discrete-time systems. Therefore, the use of simulation tools for reflection is not limited to the case study presented in this paper. Rather, this method can be used in other ECE courses as well as in other engineering disciplines that rely on simulation.

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