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Elevating Learner Achievement Using Formative Electronic Lab Assessments in the Engineering Laboratory: A Viable Alternative to Weekly Lab Reports

Baiyun Chen, Ronald F. DeMara, *Senior Member, IEEE*, Soheil Salehi, *Student Member, IEEE*, and Richard Hartshorne

***Abstract*—A lab pedagogy interweaving weekly student portfolios with onsite formative Electronic Laboratory Assessments (ELAs) is developed and assessed within the laboratory component of a required core course of the Electrical and Computer Engineering (ECE) undergraduate curriculum. The approach acts to promote student outcomes, and neutralize academic integrity violations, while refocusing instructor and teaching assistant roles towards high-gain instructional activities, such as personalized student tutoring. A mixed-method study evaluated the learning effectiveness and student satisfaction using bi-weekly ELAs versus traditional lab reports in a large-enrollment (N=68) undergraduate computer engineering laboratory course. The results of the evaluation indicate statistically significant effects on both learning outcomes and student satisfaction towards the use of formative assessments in laboratory delivery, which were corroborated by the instructor's reflections. Students in the Electronic Lab Assessment with Tutoring Enabled Delivery (ELATED) cohort performed better on the post-test and were more satisfied with the lab assessment design and assistance received in lab than those in the Control cohort. The findings offer a promising alternative for ECE and engineering lab instruction that fosters gains in practical skills and content mastery.**

***Index Terms*—electronic assessment delivery, formative assessment, laboratory instruction, learner remediation strategies.**

I. Introduction

WHEREAS engineering curricula benefit from a balance between theoretical concepts taught in a classroom and a hands-on practicum in a laboratory setting, innovations are sought to improve the efficacy and efficiency of the laboratory component [1]–[5]. Recent research confirms that lab instruction solidifies students' practical skills while linking theory and practice by exercising problem-solving techniques [1], [3], [6]. However, assessment strategies implemented in lab-based teaching may not fully attain the desired learning outcomes specified in engineering curricula [7]. Conventional lab assessments rely heavily on student composition of weekly lab reports, which typically focus on mundane procedural reporting. Thus, student motivation may wane, as analysis or critical thinking skills are not evaluated extensively via lab reporting tasks. Additionally, the time consuming nature of grading lab reports results in students receiving detailed feedback significantly after the submission period closes, which can diminish the instructional effectiveness of such feedback [7].

This paper presents an overview of *Electronic Lab Assessment with Tutoring Enabled Delivery (ELATED)* as an alternative assessment strategy, supplementary to technical report writing within undergraduate engineering labs. Research objectives evaluated via a mixed-method study herein include:

1. Comparing the effect of formative Electronic Lab Assessments (ELAs) on students' learning achievement compared to conventional lab reports,
2. Comparing students' satisfaction with an interwoven formative assessment strategy of portfolios and ELAs versus traditional lab reports, and
3. Investigating the components and distribution of laboratory teaching workloads when using the proposed and conventional assessment strategies within large-enrollment foundational computer engineering laboratory instruction.

The organization of the paper is as follows. First, a review of teaching strategies for lab instruction documented in the literature and the applicable Learning to Mastery Framework is provided in Section II. Sections III and IV discuss the context and the method of the study, respectively. In Section V, the quantitative and qualitative results of the research are presented. Finally, implications and conclusions of the work are outlined in Section VI.

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II. Review of Literature

A. Engineering Laboratory Teaching & Lab Report

Laboratory instruction is a vital component of engineering education [1]–[3]. The practical lab work is designed to engage students in the curricula and help them advance towards the objectives of gathering and interpreting experimental data, measuring performance against specifications, developing problem solving techniques, gaining practical skills, and relating theory and practice [1], [3], [6].

In a routine computer engineering lab class, students work in a cohort, follow a lab manual, set up a circuit, test items required in the manual, analyze results, and then submit a lab report documenting the entire process [6]. A typical computer engineering lab report consists of a project introduction, a proposed design with either schematics or flowcharts, narrative description of the design, prototype coding, a testing plan, and output results [8].

The traditional lab report assessment process, however, has been commonly perceived and widely documented to exhibit challenges in fully promoting critical thinking skills or garnering student engagement and enthusiasm in their learning [7], [9]. Specifically, certain pitfalls are common, including that students may repeat prompts from the lab manual without cognitively engaging in the problem-solving process. Other students may submit the lab report, yet fail to retain critical aspects of the laboratory experiment. Additionally, providing comprehensive report feedback is a very time consuming effort, often resulting in overly delayed time to feedback. This is problematic as, while some delay in lab feedback is useful to allow for reflection, significantly delayed feedback can be detrimental to the learning process, as it often results in student failure to utilize the feedback process as an instructional tool for continuous growth and progress [10]–[12]. Nonetheless, the ability to create technical reports is a vital engineering skill and Bachelor's degree accreditation criterion. Hence, the strategy developed herein retains formal technical reports once per month, which utilize a professional-grade document structure to elicit the documentation of design elements and enforce a robust scoring rubric, while remaining tractable to administer and grade.

B. Using Formative Assessments for Mastery Learning in Engineering Education

Formative assessments generally refer to diagnostic-process evaluations of student comprehension, learning needs, and academic progress during a course, and may include in-class quizzes to generate incremental feedback on performance for improving learning [13], [14]. When utilized frequently and supplemented with rapid and thorough feedback, formative assessments are particularly effective in supporting and moderating mastery learning [13], [15], [16]. Known as the *Testing Effect* [17], [18], providing learners with retrieval practice through closed-book recall assessments such as proctored quizzes, rather than open-book efforts [19], [20] such as lab reports, improves the learning environment and enables mastery learning, even for complex concepts and material [18], [21], [22].

Instructors can examine formative assessment data for evidence of students not meeting identified learning goals, and modify instructional approaches, content, and cadence, accordingly. While research related to the use of quizzes and alternative formative assessments in laboratory courses has been neglected [23], quizzes and formative assessments have been documented to exhibit a high degree of correlation with overall course grades and content knowledge acquisition in traditional STEM courses, as well as other areas [24]. Further, documented studies of the benefits of frequent online evaluation at the college-level have indicated significant increases in student performance on summative evaluations [25], [26]. In lab settings, however, the use of quizzes and formative assessments as predominant assessment approaches is less common than in other areas of study [27]. However, as illustrated in Keller's study [28], quizzes and formative assessments, in conjunction with summative assessments, can be powerful tools for identifying areas of difficulty for learners.

Students benefit from formative assessments through the specific and structured feedback regarding areas of mastery [25], as well as areas needing improvement [28]. Formative assessment strategies have been further enhanced by rapid feedback [10], [11], which has been made possible via electronic assessments, enabling students to both correct misconceptions, as well as deepen their understanding within the workload constraints of the instructional staff available.

TABLE I
Lab Assessments

Schedule	ELATED Cohort	Control Cohort
Week 1	Pre-test	Pre-test
Week 2-15	A total of 5 bi-weekly- **electronic lab assessments with submissions of lab portfolio** 2 monthly technical reports	A total of 5 bi-weekly **lab reports** 2 monthly technical reports
Week 16	Post-test Capstone project report Extra credit survey	Post-test Capstone project report Extra credit survey

TABLE II
QUESTION CATEGORIES AND THEIR CORRESPONDING LEARNING OUTCOMES

QUESTION CATEGORY	LEARNING OUTCOME
Design, Synthesis, and Debugging Tools	Identify correct syntax of MIPS Assembly Instructions and use of console commands to operate MARS development environment
Input / Output Operations	Demonstrate proficiency with parameters of the **`syscall`** command
Arithmetic Operations: e.g. **`add, addi, sub, subi`**	Compose MIPS Assembly code cable of increment and decrement operations for scalars, arrays, and pointers/strings
Program Control Flow: i.e. **`beq, beqz, bne, bnez, bge, bgt, ble, blt, j`**	Structure conditional and unconditional control flow patterns necessary for if-then, if-then-else, and looping constructs
Data Representation: i.e, ASCII, integer, binary, float	Express data values in corresponding 32-bit field formats
Data Transfer Operations: i.e. **`sb, lb, sw, lw`**	Demonstrate ability to transfer data/to from memory, including traversal of data structures in memory and access register contents
Energy Efficiency and Execution Time Analysis	Optimize MIPS assembly code efficiency in terms of energy, static instruction count, and dynamic instruction count

The use of formative assessments is particularly effective in science and engineering education [3], [14], [24], [29]. For instance, formative assessments have been shown to be useful for gaining, refocusing, and extending student attention [26], [30]. Thus, we adopted electronic formative assessments in the laboratory component of an undergraduate computer engineering course as a vital element to replace traditional weekly lab reports, in an effort to increase students' engagement, inspire creativity, and facilitate mastery learning.

III. THE CONTEXT OF THE STUDY

This paper examines the use of formative assessments in a large enrollment undergraduate laboratory of a computer engineering course at the University of Central Florida (UCF) during the Summer 2016 semester. This lab component is part of the required gateway undergraduate *Computer Organization and Design* course, EEL3801, at UCF.

A. EEL3801 Lab Description

The objective of the laboratory component is to impart hands-on experience with the fundamental devices of a computer system, the operation of processor/memory/buses, machine instruction syntax and semantics, and input/output/flow control using software simulation tools and/or FPGA case studies for the MIPS processor architecture, following a progression of topics in the fifth edition of the popular Patterson and Hennessey textbook [31]. The three-hour weekly lab consists of practical experiments that cover the theoretical concepts taught in parallel with the main course, over a 16-week period, during each of the spring, summer, and fall semesters. The course is taught by one instructor with the support of two Graduate Teaching Assistants (GTAs) who conduct the laboratory sessions, grade laboratory portfolios/reports, and provide tutoring of laboratory concepts. The enrollment is typically between 120 and 140 students each spring and fall semester, and between 65 and 75 students during summer semesters; divided into two or four lab sections with enrollments of 35 students each, to accommodate the capacity of lab facilities available.

B. EEL3801 Lab Assessments & Learning Outcomes

The overall instructional goals of the laboratory include: 1) Students consistently demonstrate their ability to identify and design the five basic components of a computer system: Input, Output, Memory, Datapath and Control; and 2) Students demonstrate professional technical communication skills. The tests and quizzes are designed to address Goal 1 and the monthly technical reports utilized in the ELATED approach are designed to address Goal 2. These were evaluated using quantitative measures based on a partial credit question scheme for Goal 1 and an explicitly defined rubric for Goal 2. To achieve these two goals, the EEL3801 lab assessment protocol consists of a pre-test, a post-test, a series of formative ELAs or lab reports, two monthly technical reports, and one capstone technical report, as listed in Table I. The tests were designed to evaluate students' laboratory solving skills; the formative ELAs were created to support and moderate mastery learning; and the technical reports and capstone project were designed to evaluate students' technical writing skills.

Students were assessed in the pre-test and post-test on their laboratory skills related to the seven learning outcomes illustrated in Table II. The questions from the ELAs were selected from separate question banks that cover only one or two of the learning outcomes. Table II lists all question categories of the question bank for the pre- and post-test and their corresponding learning outcomes.

Figure 1 shows three sample questions from ELAs that correspond to various learning outcomes presented in Table II. Figure 1a depicts an example question, which evaluates the learners' level of comprehension on the subject of Program Control flow and

Data Representation. Figure 1b illustrates the goal of evaluating the learners' understanding of Arithmetic Operations within

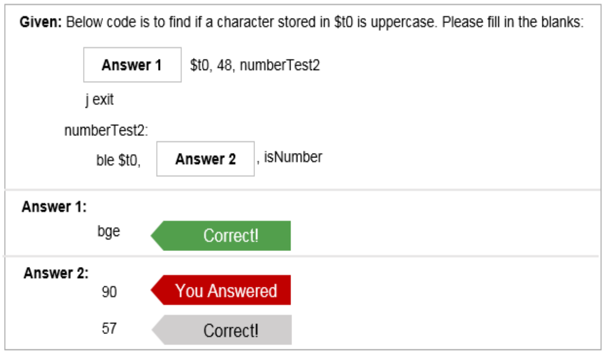

Fig. 1a. Example question on Data Representation topics.

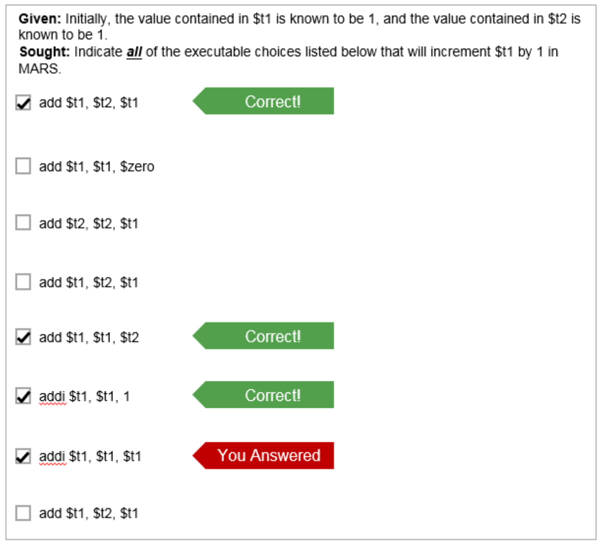

Fig. 1b. Example question on Program Control Flow topics.

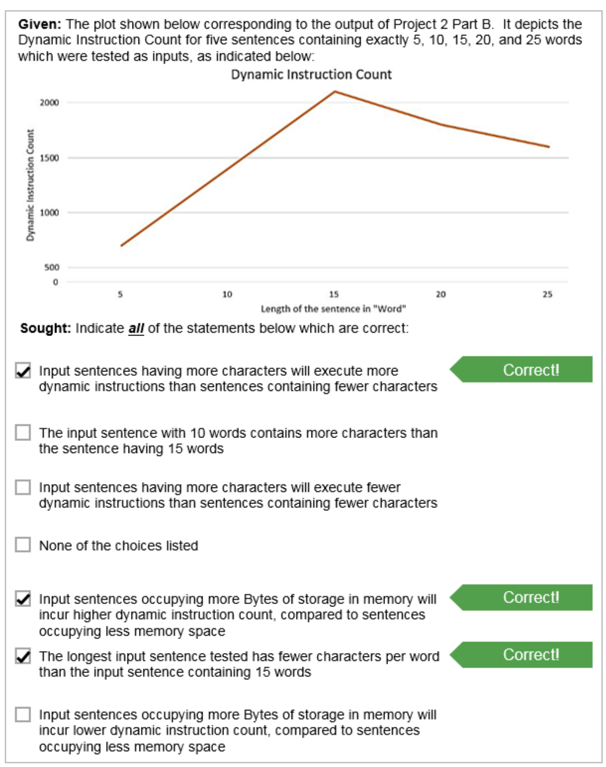

Fig. 1c. Example question on data transfer and data representation.

assembly language. In Figure 1c, an example question is provided that covers the learner's understanding of Data Transfer Operations and Data Representation combined. Each question, as shown in Figure 1, has multiple-choice options and utilizes multiple answers and fill in the blank formats for numeric answers within a specified tolerance, which is typically 5%. Together with roughly five clones of each question which provide variations in numeric values and/or phrasing, these combine to reduce the impact of guessing and crosstalk between lab sections to obtain a more realistic assessment of learning, as compared to lab reports. In addition, a variety of question types such as comprehensive questions, as shown in Figure 1c, and syntax questions, as shown in Figure 1a and Figure 1b, assist to increase coverage of topics in the lab by gaining a more precise assessment of students' understanding from the fundamentals to applied skills.

To actively neutralize potential academic violations, Internet Protocol (IP) restrictions and lockdown browsers are utilized to ensure the integrity of ELA delivery. ELAs are also proctored by the GTA present during the lab session. Additionally, privacy filters are used, which restrict visibility to a 33-degree viewing angle to secure screens from adjacent lab stations. Furthermore, in the conventional method, students' lab reports are easily replicated/shared, which reduces their learning impact. Due to the presence of ELAs instead of weekly lab reports, only those students who perform the lab assignments themselves and fully understood the concept are able to receive full credit, which increases the integrity by helping students focus on learning the material rather than copying other students' work, which is prevalent in the conventional approach.

C. EEL3801 Lab Procedures

The summer 2016 lab offering was partitioned into two sections, a Control cohort and an *Electronic Lab Assessment with Tutoring Enabled Delivery (ELATED)* [8] cohort. During the first week of the semester, students of both cohorts took a pre-test of five questions covering the lab materials and experiments, which were randomly selected from a question bank. Each week, students attended a 3-hour lab session, and were required to submit lab assessments every other week. Students in the Control cohort were assigned traditional bi-weekly lab reports, following a rubric prepared by the lab instructor, and received detailed feedback based on the rubric from the instructor in the week after each submission. The lab report's format consisted of an introduction, detailed narrative about a proposed plan and solution to the project, prototype coding, learning outcome summary, use of test cases to provide proof of functionality of submitted solutions, and references.

As illustrated in Figure 2, there are weekly and monthly activity flows. Each week, students are asked to write a free-form narrative portfolio during the lab session, which is primarily focusing on how they approached and performed the experiment. It allows for creative expression regarding how they have completed the lab tasks that they were asked to perform. Portfolios are then graded rapidly with a 2/1/0 scoring rubric in which 2 denotes *complete*, 1 denotes *incomplete* and 0 indicates *no submission*. A portfolio receiving a *complete* score provides evidence that all lab exercises were conducted via the methods covered by the lab GTA (even if some of the results were incorrect). A portfolio receiving an *incomplete* score lacks evidence for conducting one or more lab exercises via the methods covered by the lab GTA. Finally, a score of *no submission* corresponds to the lack of a portfolio submission during the enrolled lab period, or a highly deficient submission in which the learner did not provide evidence of conducting at least one of the lab exercises by engaging the methods covered by the lab GTA.

Students in the ELATED cohort were required to take a 20-minute in-lab *Electronic Lab Assessment (ELA).* Throughout the semester, there are 5 or 6 ELAs related to the previous session's tasks and experiments, each consisting of 5 to 10 items. After completing the ELA, students received an immediate score and targeted structured feedback in the laboratory. To review their ELAs, resolve misconceptions, and clarify solution procedures prior to the following week's lab session, learners are encouraged to meet with their GTA during extended office hours, which are possible due to reduced grading workloads. This allows for common mistakes to be resolved immediately, without the need to wait for an extended grading period. This was beneficial in that it allowed for assessment of the expected learning outcomes from the previous week to be assimilated. Further, GTA workload reallocation allows for more time to support of learners' individual needs, based on the student's quiz result.

As shown in Figure 2, the ELATED assessment flow includes weekly free-form portfolios and structured ELAs, along with monthly technical reports. After completing four weeks of experiments, the students in both cohorts were also required to compose a professional-grade technical report. This monthly technical support document structure elicits documentation of creative design

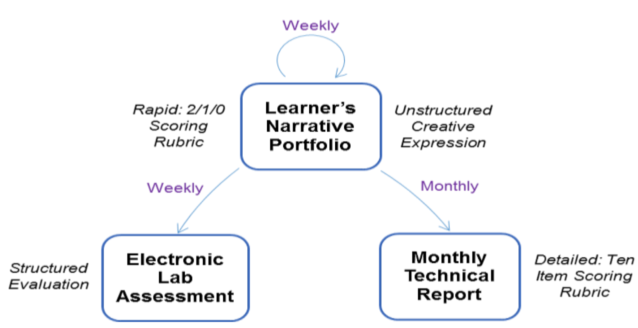

Fig. 2. ELATED assessment flow

elements. It specified their design, tradeoffs, and test cases, and was scored based on a robust rubric to refine their technical writing skills. The three technical reports, each assigned monthly, are sufficient for students to learn how to compose technical reports. Moreover, it significantly reduces the overhead effort associated with weekly lab reports and instead focuses student, instructor, and GTA time more efficiently. Results provided herein indicate that this ELATED approach can achieve the objective for the student to still acquire skills of writing technical reports. In particular via the LMS, students are provided with positive examples of report submissions from previous semesters, along with a detailed monthly report rubric, as shown in Figure 3. Upon conclusion of the course, students in both cohorts completed a post-test of five questions randomly selected from the same question bank used for the pre-test, as well as a capstone project report.

IV. Method

To compare the impact of formative assessments and lab reports on student learning, a quasi-experimental design with intact classes was used as part of this mixed-method study. Students in the ELATED cohort took five formative ELAs one week after completing lab activities. Students in the Control cohort submitted five lab reports. The specific research questions evaluated were:

1. Is there any difference in the learning outcomes between students in the ELATED and Control cohorts?
2. Is there any difference in students' satisfaction level of the lab assessment method between students in the ELATED and Control cohorts?
3. How is the instructor's time used differently between the ELATED and Control cohorts?

To answer the first two research questions, we collected test scores and survey results to address the following hypotheses:

1. *Null hypothesis I:* There is no difference in the learning outcomes between students in the ELATED and Control cohorts.
2. *Null hypothesis II:* There is no difference in students' satisfaction level of the assessment method between students in the ELATED and Control cohorts.

We analyzed the GTAs' time log to answer the third research question. In addition, we reviewed the instructor's teaching reflection log to validate the quantitative results.

A. Participants

The population of the study included 70 undergraduate students enrolled in two sections of a computer engineering lab. Among the participants (aged 19-35, M=22.59, SD=3.34), 83% (n=58) were males and 17% (n=12) were females. 40% of the participants were (n=28) White, 33% (n=23) Hispanic, 16% (n=11) Asian, and 9% (n=6) African-American. Seniors accounted for the majority 84% (n=59) of the participants. The remainder were juniors 13% (n=9) or second degree students (n=2). All students were either Electrical Engineering (n=36) or Computer Engineering majors (n=34).

The two lab sections were identical in content and taught by the same instructor, except that portions of the lab assessments varied. Students self-enrolled into the lab section, and all agreed to participate in the study. Since two students failed to participate in most assignments in the ELATED cohort before the course ended due to personal reasons, a total of 68 students participated in the study, with 33 in the ELATED cohort and 35 in the Control cohort.

- **Professional preparation: [5 points total]**
- **Report Content: [95 points total]**
  - **1.0 Project Description:** ...
  - **2.0 Program Design:** narrative description of how your code operates, and a flowchart with sufficient explanation about the program design for someone else familiar with MIPS to be able replicate your design [20 points]
  - **3.0 Symbol Table:** ...
  - **4.0 Learning Coverage:** provide a meaningful list of at least 5 technical topics learned that you could mention in a job interview. [10 points]
  - **5.0 Prototype in C-language:** ...
  - **6.0 Test Plan:** provide details identifying the inputs chosen to test the program and why these were selected, and justification why they provide adequate test coverage. [10 points]
  - **7.0 Test Results:** ...
  - **8.0 References:** ...

Fig. 3. Excerpt of the Rubric Applicable to Monthly Formal Reports.

B. Data Collection & Analyses

Both quantitative and qualitative data were collected. Quantitative data was collected through students' assessment scores, self-reported survey results, and the GTAs' time log. Qualitative data was collected through the instructor's reflection. The qualitative data was used to interpret and provide support for the results from the quantitative analyses for research question 3.

1) Learning Outcomes

With students' permission, we de-identified student scores of the pre-test, the post-test, monthly technical reports, and the capstone report project from the LMS. To analyze the differences in learning outcomes between the ELATED cohort and the Control cohort, statistical procedures, including descriptive analysis and Analysis of Covariance (ANCOVA) were conducted. Means, standard deviations, and effect sizes were computed for each test and report assignment. An ANCOVA was conducted to compare post-test scores and the scores of the report assignments between the two cohorts, using the pre-test score as a covariate.

2) Student Survey

An anonymous IRB-approved online survey was released at the end of the semester to gather student feedback from both cohorts. Thirty-two surveys were received by students in the ELATED cohort and thirty-six surveys were received by students in the Control cohort, which included one duplicate submission that was unidentifiable due to survey anonymity.

The survey consisted of thirty Likert-scale (1="Strongly Disagree"; 5="Strongly Agree") items designed to measure students' perceptions of the lab assignment design, the usefulness of the lab activities, instructional resources, and GTA assistance, as listed in Table III. The reliability measures for the survey instrument were acceptable, as the Cronbach's alpha of all variables were greater than 0.75 [19]. Independent t-tests were conducted, comparing the measure scores between the ELATED cohort and the Control cohort.

TABLE III
MEASURES OF THE STUDENT SURVEY

Measures	Definition	N of Items	Cronbach's alpha
Lab assessment design	Perceptions towards lab reports vs electronic quizzes.	7	0.757
Usefulness of lab activities	Perceptions towards usefulness of the lab activities.	8	0.849
Instructional resources	Perceptions towards resources, e.g. quizzes, videos, feedback.	10	0.800
GTA assistance	Perceptions towards the GTAs' assistance.	5	0.832

3) Instructor Reflection

In addition to survey responses, we collected the instructor's reflection regarding assessment strategies in lab teaching. The GTAs took field notes and maintained a log of how their time was used in tutoring, communicating with students, and grading. Derived from notes and the time log, the instructor composed a reflection. An analysis of the time log and reflections are reported in Section V.

V. RESULTS

The results of the research are presented in this Section to answer the three research questions. In brief, students in the ELATED cohort performed better on the post-test and were more satisfied with the lab assessment design and assistance received in lab than those in the Control cohort. The GTAs' time was used more efficiently during tutoring students within the ELATED cohort than within the Control cohort.

A. Learning Outcomes

RQ1: Is there any difference in the learning outcomes between students in the ELATED and Control cohorts?

Results of the one-way ANCOVA determined a statistically significant difference on students' post-test scores, after controlling for pre-test scores, $F(1, 60)=23.42$, $p<.001$, $\eta_p^2 = 0.281$, between the ELATED cohort and the Control cohort. As a result, null hypothesis I was rejected. Additionally, there is a high effect size ($\eta_p^2 = 0.281$) associated with the use of formative ELAs [32]. Table IV demonstrates the means and standard deviations of the pre- and post-test scores. In particular, an identical testing mechanism was deployed for both pre- and post-test. These consisted of randomized selection from a bank of questions assessing the learning outcomes listed in Table II. Understandably, scores on the pre-test were commensurate with random guessing for both Control and ELATED cohorts. However, scores on the post-test considerably diverged between the two cohorts, as described in detail in this Section.

TABLE IV
MEANS & STANDARD DEVIATIONS OF PRE-& POST-TEST

		COHORT	
		CONTROL	ELATED
Pre-test	Mean	20.39%	20.86%
	SD	15.89%	17.25%
	N	34	33
Post-test	Mean	52.14%	75.30%*
	SD	19.80%	18.37%
	N	32	33

*p<0.001.
Full scores of pre-test and post-test are 100%.

Using ANCOVA, we also analyzed the scores of all report assignments. Even though the scores for the ELATED cohort were slightly lower on all reports than for the Control group, results of analysis illustrated that there was no significant difference in scores of the Monthly Technical Report 1 ($F(1, 64)=2.314$, $p=0.133$, $\eta_p^2 = 0.035$), Monthly Technical Report 2 ($F(1, 62)=0.411$, $p=0.524$, $\eta_p^2 = 0.007$), or the Course Capstone Report ($F(1, 62)=0.452$, $p=0.504$, $\eta_p^2 = 0.007$), and the effect sizes were very small. Table V summarizes the means and standard deviations of the scores of all report assignments. Insights from the laboratory instructors suggest a possible reason for this trend. Namely, students composing reports within the Control cohort tend to recycle the lab instructor's corrections from all of their weekly reports to paste them into their semester report verbatim, without fully comprehending the full deep-learning benefit of what is contained within their final report. ELATED can result in higher-gain utilization of students' and graders' time towards achieving a deep-learning outcome, as such was borne out by the analytics of the summative assessment. Meanwhile, scores associated with reports may not be reliable indicators of deep-learning outcomes.

TABLE V
MEANS & STANDARD DEVIATIONS OF REPORT ASSIGNMENTS SCORES

		COHORT	
		CONTROL	ELATED
Technical Report 1	Mean	89.41%	83.88%
	SD	12.544%	16.693%
	N	34	33
Technical Report 2	Mean	94.44%	93.10%
	SD	7.605%	9.676%
	N	34	31
Capstone Report	Mean	82.35%	79.55%
	SD	18.560%	14.537%
	N	34	31

Full scores are 100%.

B. Student Satisfaction

RQ2: Is there any difference in students' satisfaction level of the lab assessment method between students in the ELATED and Control cohorts?

Students in both cohorts rated their experience with the lab environment and instructional resources very high, with scales greater than 4 on the 5-point Likert Scale, as listed in Table VI, which summarizes the means and standard deviations of all scales. However, there were statistically significant higher ratings with the ELATED cohort on the scales of lab assessment design, i.e. $t(66)= -2.378$, $p=0.020$, and GTA assistance, i.e. $t(66)= -2.492$, $p=0.015$. Therefore, null hypothesis II was rejected. There were

TABLE VI
MEANS & STANDARD DEVIATIONS OF SURVEY MEASURES

		COHORT	
		CONTROL	ELATED
Lab assessment design	Mean	3.63	4.05*
	SD	0.817	0.627
	N	36	32
Usefulness of lab activities	Mean	4.07	4.34
	SD	0.680	0.553
	N	36	32
Instructional resources	Mean	4.07	4.16
	SD	0.641	0.579
	N	36	32
GTA assistance	Mean	3.58	4.09*
	SD	0.921	0.745
	N	36	32

*p<0.05.

also statistically significant differences in students' attitudes towards the assessment design and GTA assistance between students in the Control cohort and the ELATED cohort.

Figure 4 shows the student self-reported responses to sample questions related to assessment design. Using the 5-point Likert Scale, students in the ELATED cohort mostly agreed that the ELAs were reasonably fair, i.e. phrased clearly and adequate time was allowed (M=3.96); completing concise ELAs was preferable to submitting weekly lab reports (M=3.94); and electronic questions were adequate to evaluate engineering design skills (M=3.88).

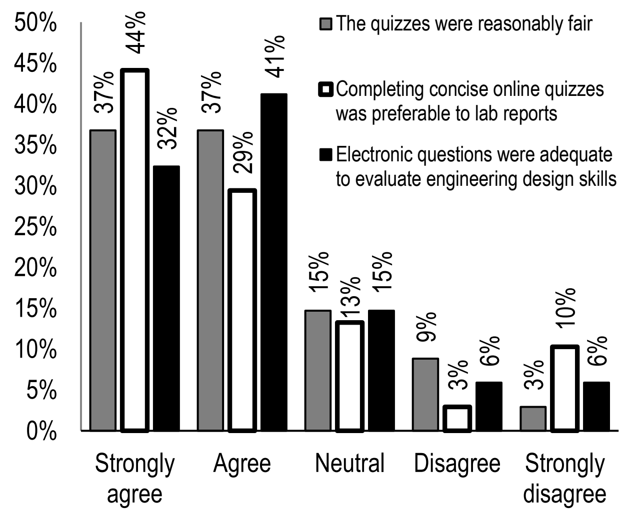

Fig. 4. Self-reported responses to sample survey questions related to assessment design.

Figure 5 shows the student responses to sample questions related to GTA assistance. Using the 5-point Likert Scale, students in the ELATED cohort mostly agreed that GTAs' guided access to quiz results enhanced their comprehension (M=4.19); GTAs' guided access to quiz results enhanced their confidence to solve and/or communicate about engineering problems (M=4.19); and the GTAs maintained an effective environment for learning (M=4.09). Whereas the question bank is secured such that ELAs are viewable under GTA-controlled password-protected access, students are afforded various opportunities to review their submissions with the GTAs. These include one-on-one review during the laboratory session with the laboratory GTA, during the office hours of the laboratory GTA, and within an open tutoring center already operated at the college-level. The tutoring provided during GTA-enabled review includes solving any missed problems together with the student, answering the student's questions, and elaborating applications of the material in other contexts via internet search engines. The latter occurs in real-time to identify relevant supplemental web-based resources and instructional videos on YouTube that resonate with the student.

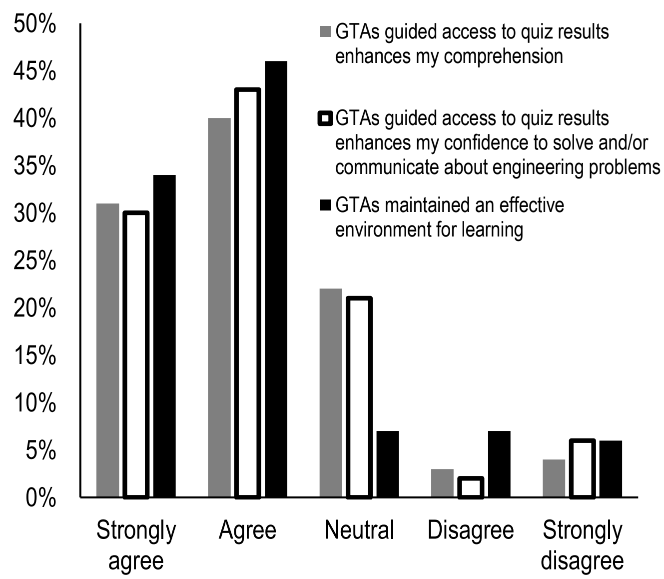

Fig. 5. Responses to sample survey questions related to GTA assistance.

C. *Instructor Feedback*

RQ3: How is the instructor's time used differently between the ELATED and Control cohorts?

To answer the third research question, we analyzed the GTAs' time log and the instructor's reflection. The results indicated that the GTAs' time was used more efficiently during tutoring students with the ELATED cohort than with the Control cohort. For instance, each week the GTA spent 11 hours grading the lab reports and 1.1-hour answering student questions via emails for the students in the Control cohort. For students in the ELATED cohort, the GTAs only spent 2.5 hours grading the major reports and portfolios and had 27.5 hours allocated for tutoring, which was more than 1.5 times more hours available out of their 30 hours per week than the Control cohort, as depicted in Figure 6. As reported in the GTAs' time log, there was an insignificant amount of email communication explaining content to the ELATED cohort. This is commensurate with the students' routine visitation with the GTA due to increased tutoring hours. Further, the GTAs indicated that there were 13 instances of repeating information addressed in class or online for the ELATED cohort and 63 such instances for the Control cohort. Based on the number of repeated questions from students, it appeared that students in the ELATED cohort comprehended information more fully than in the Control cohort.

The instructor reflected that using ELATED, the lab GTAs' workload becomes more focused on assisting students based on their knowledge/skill gaps, rather than mundane activities of grading weekly lab reports. As shown in Figure 6, approximately 10 hours per week were reallocated to assist learners facing challenges regarding the subject matter of the experiments, which made a significant impact in the ability to assist each student in labs having large enrollments. Essentially, the time that was spent grading lab reports is utilized for tutoring and obtaining a clearer identification of each student's true grasp of the concepts for each project. Accurate assessment of achievement is fortified through the increased integrity of ELATED compared to conventional lab report submissions, while engaging the *Testing Effect* [17], [18]. Students have also verbalized their satisfaction with the ELATED method, since they are not burdened to compose weekly lab reports in which they report low gains in learning, thus freeing time to study and also resolve concerns with help from the GTAs/instructor, who has more time available to assist due to reduction in grading load of lab reports.

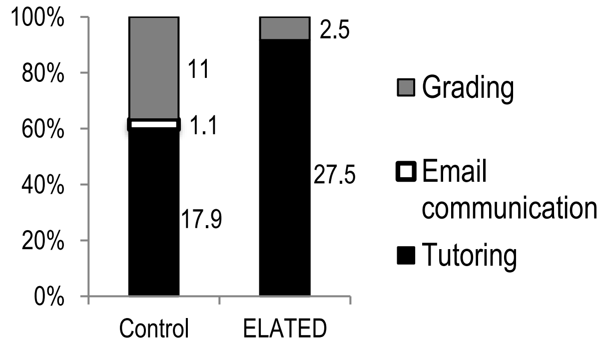

Fig. 6. The GTAs spent significantly more time (hours per week) for tutoring than grading in the ELATED cohort.

The lab instructors' feedback regarding ELATED was positive for increased attainment of the learning outcomes identified in Table II, reduction of logistical burden, and increased time for tutoring. Instructors indicated that ELAs tended to benefit two groups of students compared to lab reports. The first group of students were those who successfully finished their tasks and used ELAs as a review by invoking the *Testing Effect* [17], [18] to reinforce what they have learned. The second group of students who benefitted from ELAs were those who were not able to completely assimilate skills during the lab period, and received identification of those elements where students need to seek guidance via rapid in situ identification within the lab environment. Such benefits were not attained by receipt of graded report multiple days later. Additionally, instructors reported a higher integrity level of ELAs compared to lab reports by having an adequate number of clones for each question, using IP restriction, and requiring use of lockdown browsers. Those students, who did not complete tasks on their own or attempted to copy the solution from other students or from online repositories, were precluded from improperly receiving credit. To achieve these goals, the faculty and lab graduate assistants initially composed a baseline set of ELAs that comprehensively assessed students' learning progress for each learning outcome. They then created five clones for each question during the subsequent semester, which delivered alternate numeric values in each question to reduce crosstalk between lab sessions by attaining a rich bank of alternative questions for each topic, which were disbursed at random. Instructors also reported that discussion posts, announcements, and blogs were very compatible with the ELATED approach for increasing learner-instructor interaction, while reducing delays to provide feedback. These facilitated a rapid response method so that the students did not have to wait until office hours to obtain answers to the most frequently-asked questions.

VI. Discussions & Conclusion

The findings of this study have significant implications for the utilization of electronic formative assessments as a pedagogical strategy to foster mastery learning in undergraduate engineering laboratory courses. Our research indicates frequent electronic formative assessments, immediate feedback, and targeted and personalized onsite mentoring from the instructor and GTAs resulted in significant improvements in student outcomes on hands-on problem-solving. Results also indicated that students embraced this innovative lab teaching strategy, and preferred electronic formative assessments to traditional lab reports. Further, the ELATED pedagogical framework mitigated increases in low impact grading tasks of GTAs and faculty associated with larger classes, through refocusing instructor efforts to higher impact activities, such as tutoring, tuning, and content renewal.

The use of electronic formative assessments as a laboratory instruction mechanism has been an underexplored approach. Our research supports the use of ELAs within undergraduate engineering laboratories as an alternative pedagogical approach to traditional lab assessment. Compared with traditional lab reports, the use of frequent formative assessments formally establish standards of mastery and intrinsically motivate students for mastery learning. Immediate feedback and individualized tutoring further extend the quality of lab teaching. For students who lack mastery of particular concepts, the targeted feedback via ELAs immediately reveals both strengths and misconceptions. In an effort to address areas of weakness, learners that do not achieve mastery scores are obligated to meet with a lab GTA or the instructor to review their assessment results, prior to the next week's lab session. This individualized, targeted, and structured remediation, which is difficult to accomplish in traditional lab courses, was possible due to the reallocation of instructor and GTA workloads. Finally, technical reports assigned monthly, which accumulated portfolio entries within a formal engineering design specification format, were found to elicit more focused technical communication skill development than conventional weekly lab reports.

In the conditions of our case study, the lecture component was identical for both Control and ELATED cohorts, i.e. both cohorts were exposed to online quizzes being delivered via lockdown browsers in Canvas using the same interface to deliver the ELAs. This occurs due to the exclusive use of computer-based quizzes and exams within all formative and summative assessments in the lecture component [33]. The pre- and post-tests are taken from the same question bank, however, the formative ELAs are not. In particular, each ELA is associated with its own question data bank. There is no statistically significant difference between the two cohorts on the report assignments even though the Control cohort completed more lab reports throughout the semester.

Innovations in laboratory instruction are urgently needed to address the increasing enrollments of undergraduate engineering courses. Our research is an endeavor toward providing a more effective lab pedagogical framework while maintaining appropriate instructor workloads [34], thus rendering a potentially transportable benefit for laboratory teaching and learning across engineering and related fields.

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