2021 ASEE ANNUAL CONFERENCE
Virtual Meeting | July 26–29, 2021 | Pacific Daylight Time
Paper ID #33345

Remote Versus In-hand Hardware Laboratory in Digital Circuits Courses

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Abstract

The COVID-19 pandemic has isolated many engineering students at home and complicated access to instrumentation and hardware resources necessary to support laboratory courses. One viable alternative to bringing the hardware to students (and the correspondingly high overhead associated with shipping laboratory kits all over the world) is to enable remote access to that hardware. A remote lab allows students to access real hardware physically located in a single location from anywhere in the world. Advances in cloud computing allow students to take advantage of a full-fledged remote experience without compromising what they could have accomplished if they were physically present in the lab. While remote access laboratories are not new, the COVID-19 pandemic has enabled a unique opportunity to compare learning with how remote access to real hardware vs. hands-on access to the same hardware. Comparisons between the two modes of learning were made for a junior level course in digital circuit design using field programmable gate array (FPGA) hardware offered via remote access in autumn 2020 and via hands-on access in the same course in winter 2020. Detailed assessments of student work were grounded in Bloom's Taxonomy to classify the complexity of student cognition and learning. This study presents assessment results associated with a single laboratory assignment that was the first in a series of laboratory assignments in the digital design course. Work from 41 students from each offering were analyzed within the first five levels of Bloom's Taxonomy. Results show that students performed significantly better in terms of *overall* scores and *analyze* skills when presented with remote access to laboratory hardware than when having that hardware in hand. Comparisons between the two settings in the remaining four levels of Bloom's Taxonomy (remember, understand, apply, evaluate) were not significantly different between the two offerings. These results complement other studies that highlight the benefits of remote laboratories. Accordingly, the increased efficiency and cost savings of the remote lab approach can offer stable and reliable instruction well beyond the COVID-19 crisis.

Introduction

Since March 2020, the COVID-19 pandemic has affected all facets of life and has become a major disruption to higher education worldwide. Many institutions have opted to cancel in-person classes, including labs, and have mandated a pivot to online instruction to help control the spread of the virus. Researchers have studied online education for decades and research shows that effective online learning results from a planned instructional design using a systematic model for development [1]. Research also showed that educators who are new to online instruction report challenges related to increased workload, the usage of new technologies, and organizing their courses to fit asynchronous or a hybrid form of delivery [2]. These are challenges that typically occur with any gradual transition to online instruction. However, the transition that happened due to the COVID-19 pandemic was neither planned nor gradual or ordinary, and therefore the kind of instruction that followed is best described as emergency remote teaching (ERT). As defined by Hodges et al [3], ERT is a temporary shift of instructional delivery to an alternate remote delivery in the face of crisis circumstances. Due to the unplanned nature of ERT, embracing the new form of practice has confronted educators and institutions with obstacles such as making educational resources accessible to students regardless of their location. In particular, engineering courses that have hands-on lab components have faced considerable challenges in offering a similar learning experience to traditional learning when physical laboratory instruments, materials, and supplies are no longer available to students.

This study looks at the differences in learning stemming from the transition from a traditional in-person laboratory to a remote FPGA laboratory in response to COVID-19. During the initial transition to ERT in the spring of 2020, the department of electrical and computer engineering at the University of Washington, the institution involved in this study, opted to ship lab kits associated with digital circuits courses containing all essential components for the lab assignments to students at their different locations around the world. This approach was fraught with difficulty. In some cases, lab kits did not even reach students overseas due to border regulations in students' countries or other delivery failures. After spring of 2020, a new approach was warranted, one which was both viable and cost-efficient. This new approach set up FPGA boards and related equipment at the University of Washington in such a way that students could access the hardware from anywhere in the world. While this approach solved the logistics problem associated with ERT, it is not guaranteed that student learning remained stable in the transition. Thus, this paper investigates whether student learning declined, remained stable, or improved in the process of shifting to this remote laboratory paradigm.

Background

For simplicity, throughout this paper we will refer to the ERT course which offered access to FPGA hardware remotely as “remote offering” or "remote laboratory" and will refer to the in-hand access to that same hardware as “traditional offering” or "traditional laboratory".

Courses in electrical and computer engineering often include a lab component that provides students with hands-on experience in system design, programming, and problem solving. Traditionally, students receive physical lab kits and get access to lab facilities to complete their lab assignments. The transition to remote instruction due to COVID-19 urged a transition to a more stable, efficient, and reliable solution to hardware access. Accordingly, a remote lab became an appealing approach.

Remote laboratories evolved since the early 90's and they have continued to gain attention in education research since that time [4]. There have been numerous definitions of remote lab environments in the literature where the terms “remote lab” and “virtual lab” are often used synonymously [5, 6]. However, it is important to establish a clear distinction between the two terms. Virtual laboratories are simulated, non-physical environments that model a real-life lab with a computer-based application. Conversely, remote laboratories give the user the ability to access and control physical equipment from distant locations using a computer and communication infrastructure. Remote labs offer students a convenient opportunity to access equipment 24 hours a day, seven days a week without geographic proximity restrictions. This approach also promotes collaborations among peers and offers improved accessibility to students with disabilities [7]. Unlimited access to resources in the remote laboratory context could have far reaching consequences for education and can present a paradigm that promotes student-centric environments and autonomy that contributes to motivation [8]. The benefit of remote experimentation is not limited to higher education but can extend to industry and research centers, where accessing expensive and hard to acquire equipment can become more attainable. The concept of remote labs can be further extended to “distributed labs” which introduce an infrastructure that allows sharing lab resources among different universities for a more efficient use of resources. A distributed remote lab provides geographically distributed users simultaneous access to resources in real time, albeit across limited time windows. Load balance is a benefit of using distributed remote labs when labs at different universities are connected through a network. If multiple universities have copies of the same hardware lab, students are directed first to the use of the remote lab at their home institution and if the resources are not available, are then redirected to another hardware station at a different university within the network.

There are a wide range of publications on remote laboratories [9] but a relatively small subset focuses on assessing learning outcomes associated with these laboratories. Even fewer studies compare learning outcomes associated with the remote laboratory experience to that associated with the traditional laboratory experience. Nevertheless, recent reviews by Brinson [10] and Post et al [11] provide strong evidence to suggest that a large majority of non-traditional laboratories offer equivalent or better learning outcomes to students than traditional laboratories. The review by Brinson [10] included both virtual and remote laboratories where the term remote laboratory refers to a real experience and real hardware that is remotely controlled while a virtual setting refers to a laboratory where the experiment or experience is simulated (i.e., no real experiment is completed). Among 56 studies reviewed, 36 (64%) indicated that learning outcomes were better in non-traditional laboratories than in traditional laboratories while an additional 14 (25%) indicated equivalent learning outcomes between the two settings. Most studies (71%) used quizzes or tests to evaluate learning outcomes with only a small number using more comprehensive assessment techniques such as written laboratory reports (9%) or practical exams (9%). An overwhelming majority of studies (95%) also focused on content knowledge alone and did not include the assessment of inquiry, practical, perception, or analytical skills associated with these laboratories. A subsequent review by Post et al [11] included additional articles published between 2014 and 2017 but focused specifically on remote laboratories offered in higher education settings. Of the 23 studies published between 2003 and 2017, all but four were in engineering and a minority of the studies (43%) compared learning outcomes between traditional and remote laboratories. Small sample sizes (N <=50) dominated these studies with only 11 (48%) studying over 50 students. Consistent with the Brinson review [10], Post et al [11] found that most studies of remote laboratories revealed learning outcomes that were equivalent to or better for remote laboratories than for traditional laboratories; most studies used tests or surveys to evaluate learning outcomes; and the evaluation of learning benefits was primarily superficial as it was not the focus of most publications on these remote laboratories. However, the review by Post et al. [11] also evaluated behavioral and affective outcomes in remote vs. traditional laboratories in addition to cognitive outcomes. It found that students in remote laboratories tend to interact more with the lab and be more efficient in learning and perceive the remote learning experience to be at least as satisfying as a traditional laboratory experience.

This study sought to add to the existing knowledge regarding the learning benefits associated with remote and traditional laboratories by overcoming shortcomings of several previous studies into a comparison of remote and traditional learning in the ERT context prompted by the COVID-19 pandemic. This study included larger sample sizes (N = 82), compared learning outcomes in the same laboratory offered in both the remote ERT-based setting and in the traditional setting, and used laboratory reports rather than quizzes or surveys to elicit greater depth of insight into student learning. As importantly, this study used a widely accepted framework (i.e., Bloom's taxonomy) for evaluating student learning including knowledge and understanding but also going well beyond these basic levels of learning to include assessing students' ability to apply, analyze, and evaluate learning associated with these laboratories.

This study involved a single digital design course which requires students to complete lab assignments using specialized Field Programmable Gate Arrays (FPGAs) hardware that is commonly used for laboratories in digital design courses. The first laboratory in this study used a traditional hands-on lab where students had hands-on access to a physical lab kit and were able to physically interact with the FPGA hardware. The second offering used a remote lab where FPGA hardware was hosted on campus and students accessed it remotely from a wide range of locations. The lab used a distributed remote FPGA lab shared between 5 universities in 4 countries that are connected through a global network of remote laboratories called LabsLand [12].

Conceptual Framework

The assessment of student work described in this study is grounded in Bloom's taxonomy. Bloom's taxonomy is a classification of skills that divides educational objectives into three domains: cognitive, affective, and psychomotor [13-15]. The cognitive component of the taxonomy is divided into 6 levels of learning: *remember*, *understand*, *apply*, *analyze*, *evaluate*, and *create*. From a hierarchical perspective, these levels represent how people learn. Before one can *understand* a concept, they must *remember* it. Accordingly, before *applying* the concept, one must understand it and before *analyzing* it, one must be able to apply it. Similarly, a concept must be analyzed before its impact can be *evaluated*. Finally, *creating* original work requires remembering, understanding, applying, analyzing, and evaluating. At a generalized, domain-independent level and more specifically, within engineering laboratories, these six levels involve [14]:

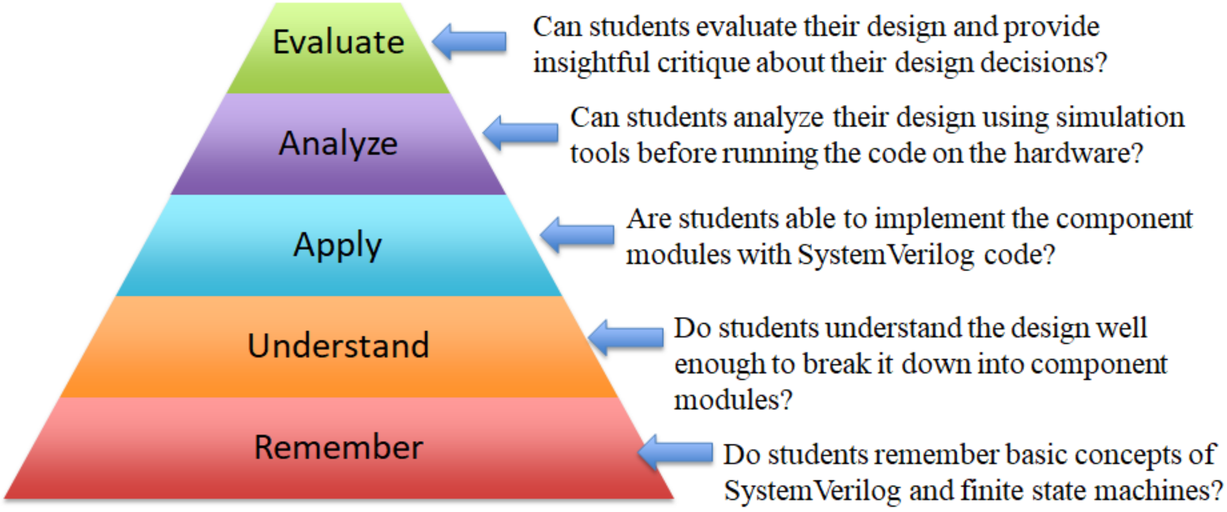
- *Remember*: recognizing and recalling basic concepts and relevant knowledge from memory. In an engineering laboratory, this level of the taxonomy focuses on content knowledge and is the primary form of learning assessed in tests, quizzes, and surveys associated with studies of remote vs. traditional laboratories [10][11].
- *Understand*: explaining ideas through oral, written, or graphic communication. At this level, insight and depth are expected and should relate to the topic or activity. A high-level understanding that relates activities and processes to purpose and objectives is expected. In engineering laboratories, the laboratory reports required to assess this level of knowledge are rarely used in studies of remote vs. traditional laboratory settings [10][11].
- *Apply*: using knowledge in new situations. This level examines the demonstration of understanding through developing content or products on the related topic. An example would be making full and appropriate use of a tool (such as a software tool) to create a product or a program. As with *understanding*, studies which measure students' ability to apply knowledge in new situations in remote or traditional laboratories are scarce.
- *Analyze*: drawing connections among ideas. In this level, concepts are broken into parts, determining how the parts relate or interrelate to one another or to an overall structure. An engineering student who has mastered this level may demonstrate adeptness at

manipulating data through visual methods such as simulation tools to show trends and to draw suitable conclusions from the data.

- *Evaluate*: Making judgements and critiquing based on criteria is expected at this level of the taxonomy. Students should be able to validate decisions and critique the accuracy of the information. Students who *evaluate* well can provide reflections on approaches taken to solve a problem and demonstrate their ability to assess underlying concepts in the process of choosing the best among multiple alternative solutions.
- *Create*: putting elements together to produce a new pattern or original work. In engineering, the previous levels of the taxonomy culminate to the design of a component or system that invokes all previous levels of the taxonomy. Such efforts to create are often stimulated in capstone design classes but can also be invoked in smaller projects in lower-level courses.

Promoting the integration, design, and evaluation capabilities of students is one of the important goals of the undergraduate engineering curriculum. Accordingly, Bloom's taxonomy has become an important tool for science and engineering educators [16][17][18] to ensure an adequate coverage of high-level cognitive skills in the curriculum in order to prepare students to effectively design engineering systems in industry [19].

The application of Bloom's taxonomy to the laboratory experiences and reports assessed in this paper is shown in Figure 1. Students are expected to enter into the laboratory with prior knowledge of Finite State Machines and the fundamentals of Hardware Description Language (SystemVerilog). The 6th level of Bloom's taxonomy was not included in the study because the outcome (goal) of the laboratory was predefined by the instruction team.



Can students evaluate their design and provide insightful critique about their design decisions?

Can students analyze their design using simulation tools before running the code on the hardware?

Are students able to implement the component modules with SystemVerilog code?

Do students understand the design well enough to break it down into component modules?

Do students remember basic concepts of SystemVerilog and finite state machines?

Figure 1. Assessment of Digital Design Laboratories using Bloom's Taxonomy

Method

This study compared student learning within the first 5 levels of Bloom's taxonomy (*remember*, *understand*, *apply*, *analyze*, and *evaluate*) in a traditional versus remote laboratory assignment in a junior level digital design course. Laboratory reports collected from a traditional and remote offering of the same digital design course, pre and during pandemic, respectively were assessed to compare learning outcomes in the two laboratory settings. Work from 82 students majoring in electrical and computer engineering department or computer science and engineering was assessed. All students were pursuing their bachelor's degrees at the University of Washington.

Setting

Student learning was assessed with respect to a single laboratory assignment that was the first in a series of laboratory assignments in the digital design course. The assignment required students to design a digital system that simulated the mechanism of cars entering and exiting a parking lot with two sensors (a and b) monitoring the cars activities (Figure 2). Students were asked to update a counter that increments as cars enter the lot and decrements as cars exit the parking lot assuming a maximum capacity of 25 cars.

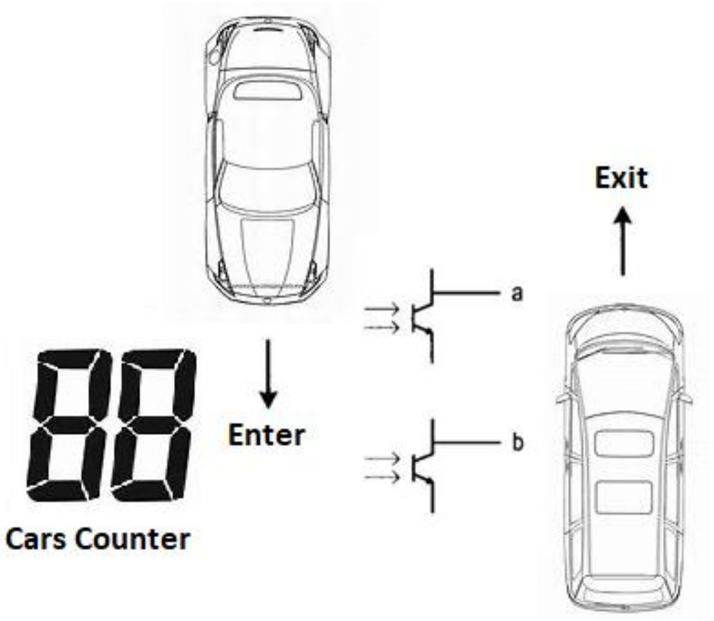


Figure 2. Parking Garage Laboratory Assignment

To implement the system illustrated in Figure 2, students were instructed to:

1. Design a finite state machine (FSM) where the binary values of a and b will mimic the entrance and exit of cars.
2. Design a counter with two control signals that increment and decrement the counter according to cars entering or exiting the lot.
3. Combine the counter and the FSM and model the parking lot, using two switches to mimic the two sensors and the seven-segment displays to display the car count.

4. Use 2 light emitting diodes (LEDs) to represent the a and b signals. When a is 1, turn on one LED (acts as a red LED), and when a is 0, turn off that “red” LED. When b is 1, turn on another LED (acts as a green LED), and when b is 0, turn off that “green” LED.

The implementation of this system required students to interface multiple switches and LEDs on a breadboard with an FPGA to model the parking lot and demonstrate a working system. The goal of the assignment was to refresh students’ experience from a pre-requisite, introductory digital circuits course by engaging them in a moderately complex digital design that uses the pre-requisite skills. Students were expected to know FSM design, breadboard wiring, and implementation of digital circuits using SystemVerilog Hardware Description Language (HDL). Additionally, students were expected to use ModelSim simulation to simulate the design before running it on the hardware.

In the traditional laboratory (winter 2020), each student received a physical lab kit to run SystemVerilog code on a DE1-SoC FPGA board. In the remote laboratory (autumn 2020), a remote lab was developed, constructed, and tested for use in the digital design course. The remote lab was installed at the University of Washington (UW) and consisted of eight DE1-SoC FPGA boards connected to an ethernet network that is part of a distributed network of FPGA labs located at five universities in four countries. The distributed remote lab builds on a previous work by Mayoz et al. [20]. One of the two structures of the remote lab is shown in Figure 3. Each structure consisted of four FPGA boards and each FPGA board has built in peripherals including switches, keys, and LEDs that are needed to run the laboratory assignment assessed in this study. The operation of the peripherals was captured by a video camera that sent video bitstream to a web server to emulate the activities of input and output to/from the board through a web interface.

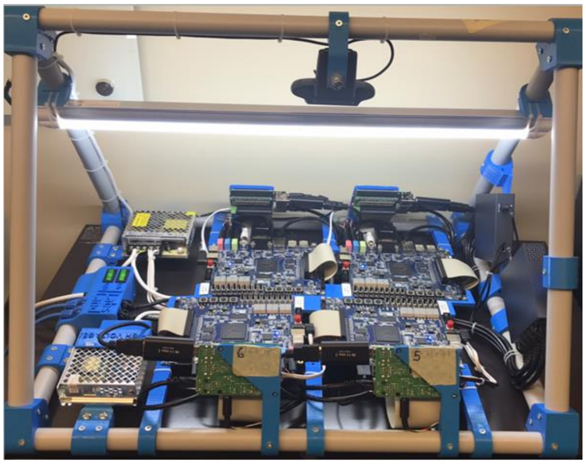


Figure 3. One of two Structures in the Remote Laboratory Set-Up.

When a student gained access to one of the FPGA boards, a real time image of the board and its peripherals is displayed through a web-based interface allowing students to use virtual input switches and keys and observe subsequent output displayed on the physical LEDs of the board (Figure 4). A virtual breadboard is also interfaced with the physical FPGA board to allow students to interface external circuitry as they would do with in-hand breadboards [21].

Students have two minutes to program the FPGA, interact with the virtual inputs and observe the output that is captured from the board by the video camera. After the allotted time has expired, the board is made available for the next student in the queue. In the autumn quarter of 2020, 60 students were enrolled in the course and the average reported wait time was less than 10 seconds. The wait time is dependent on the availability of similar labs in different locations worldwide which accommodated load sharing at different time zones.

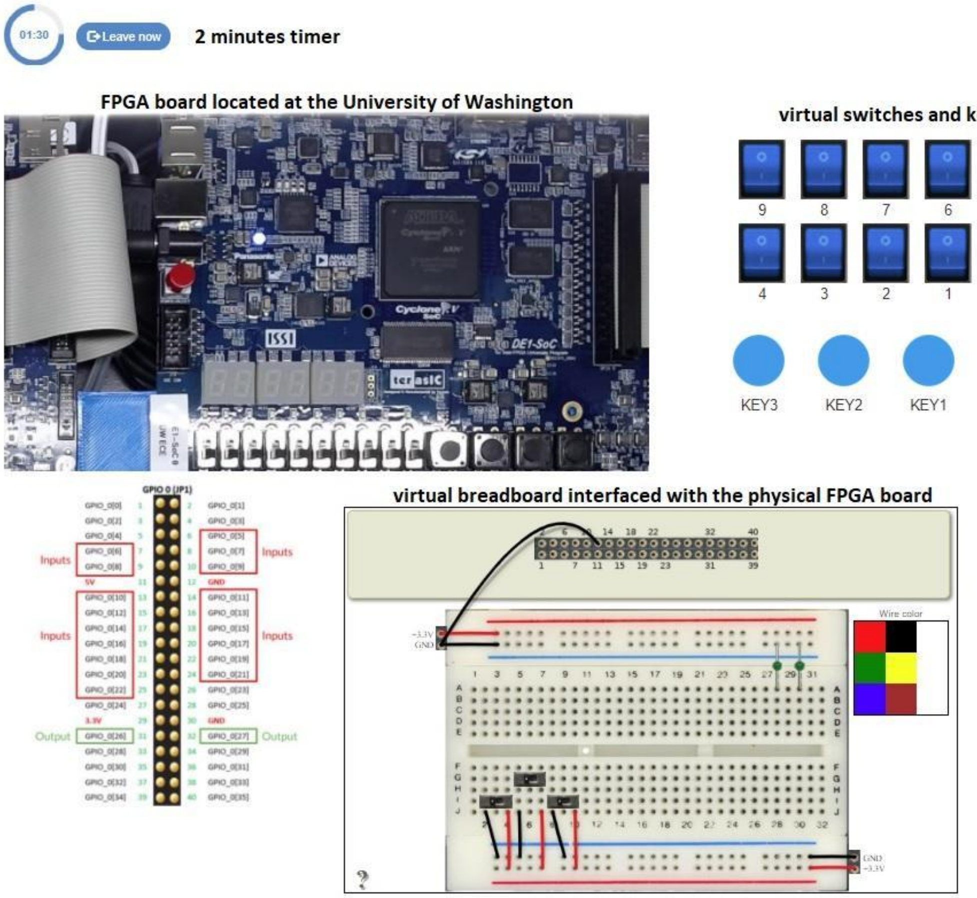


Figure 4. Interface to the Remote Laboratory

Intel Quartus version 17.1 was installed on the remote laboratory main server and students could use a code editor in the web-based IDE to write and compile code written in SystemVerilog. However, the web-based interface did not support simulation using Quartus ModelSim and therefore students worked on the code design, implementation, and simulation on their local machines and then used the web-based IDE to run the code on real FPGAs. Students were required to demonstrate their working design and complete a laboratory report associated with the assignment. The assignment was then assessed using the instruments described next.

Instruments

A grading rubric was created to measure students’ performance at each level of the Bloom’s taxonomy. The rubric is summarized in Table 1. Descriptions of each score were chosen to match the category (e.g. *remember*, *understand*) and also to reflect an interval scale such that the difference or distance between scores 1 and 2, 2 and 3, and 3 and 4 were approximately the same. This selection of rubric strategy allowed mean and standard deviation to be computed and compared between the traditional and remote laboratories using standard t-tests.

Table 1. Grading Rubric for Remote and Traditional Laboratories

Level	1 (novice)	2 (developing)	3 (competent)	4 (exemplary)
Remember	*The degree to which students remembered material from previous courses and applied it to this lab.*			
	Student presents an incomplete FSM diagram; System Verilog code contains syntax errors.	Student presents full FSM but with conceptual errors in the state diagram or in the logic of the System Verilog code	Student presents correct design of FSM and correct implementation using System Verilog, but FSM diagram has minor errors.	Student presents optimal design of FSM (i.e. minimum possible states) and implementation in System Verilog with no errors.
Understand	*The degree to which students understood the laboratory problem and broke it down into modules*			
	Student uses only one module to represent the whole design without breaking it into different components.	Student breaks the problem into modules without showing how the modules should be interconnected.	Student breaks down the design into modules with correct interconnectivity between modules, but design is not optimal.	Student uses optimal design (i.e., larges number of component modules and fewest numbers of states) with correct break-down into modules and correct interconnectivity.
Apply	*The degree to which students applied concepts of Hardware Description Language to the design*			
	Student implements design as one module in System Verilog with logical errors. Design is not functional.	Student implements different modules in SystemVerilog but the whole design is not functioning correctly.	Student correctly maps modules onto System Verilog code with implementation of a top-level module that combines all modules. Design is functional but not optimal.	Student optimally maps designed modules into SystemVerilog including the implementation of a top-level module that combines all modules. Design is functional and optimal.
Analyze	*The degree to which students effectively used simulation tools to produce a functional design.*			
	Student attempts to write a testbench to simulate the design as a single top-level design. Simulation is not functional.	Student writes testbenches for some modules but not all modules. No testbench for the top-level module is provided.	Student writes testbenches and simulating all models of the design. Simulation of all individual modules is correct but top-level module is missing.	Student demonstrates simulation of all parts of the design including the top-level module that combines all modules.
Evaluate	*The degree to which students effectively critiqued their approach to the laboratory.*			
	Student reiterates what the problem statement is about with no reflection on the approach taken.	Student describes general approach of the design with no justification of design decisions.	Student reflects on the design and simulation results. The approach to most but not all modules is justified	Student provides a detailed reflection on all aspects of the design based on the simulation results and justifies the approach, comparing intended design to actual output.

The *remember* level expects students to have prior knowledge from the prerequisite course regarding how to create a Finite State Machine (FSM) and how to implement it using SystemVerilog Hardware Description Language. This level of Bloom's taxonomy was evaluated by inspecting students' lab reports for state diagrams as well as inspecting their SystemVerilog code on the implementation of an FSM to ensure elements of the prerequisite course were included.

The *understand* level explored how well students understood the problem statement by breaking it down into independent modules. A detailed block diagram that shows the relationship between the different modules that make up the whole design was a hallmark of a high level of *understand*. Closely related to the understand level, the *apply* level expected students to transform the block diagram they developed at the *understand* level into functional SystemVerilog code that could be demonstrated in either in-hand or remote lab hardware.

The *analyze* level expected students to test each module of the design through writing a testbench for that module and simulating it on the ModelSim simulation software. One crucial piece of this level was a demonstration of simulating the top-level module that integrates the whole design. This piece was often skipped by students as they typically rely on testing the design by running it on the FPGA rather than verifying the design first. Students were expected to submit screenshots of the simulation results in their lab reports to prove their mastery of comprehensive simulation.

Finally, the *evaluate* level expected students to reflect on their design and compare the intended design with the acquired outcome. Students were expected to provide critique to their solution, consider alternative designs, and justify their design decisions.

These levels of Bloom's taxonomy were scored from 1(novice) to 4 (exemplary). Scores of 0 were given to students who provided no evidence of a particular level/skill.

Data Collection

SystemVerilog code files and a lab report were assessed to generate data for analysis in this study. In the lab report, students were asked to submit the following:

- A description of how the student approached the tasks in the assignment with an accompanying block diagram of the system and any relevant Finite State Machine diagrams. A description of major components of the system and any important features of those components.
- A discussion on how and why the student implemented the system as described.
- Screenshots of simulation results and a description of what those results demonstrate.
- A reflection on the finished system and comparison to what was expected in the lab specification.

All students in both offerings submitted the required deliverables with varying degrees of detail. A random sample of 41 reports from each offering was scored according to the grading rubric shown in Table 1.

Data Analysis

Overall scores and individual scores representing five levels of Bloom's taxonomy were analyzed using R (4.0.3 version) and R studio (version 1.4.1103). The assessment rubric was designed such that the 1, 2, 3, and 4 scores in each level of Bloom's taxonomy were both ordinal and approximately interval. Descriptive statistics were calculated for the overall scores as were skewness and kurtosis to verify normality and suitable tests for statistical analysis of the data. When assumptions of normality were justified, independent samples t-tests were used to compare the overall scores and individual scores within each level of Bloom’s taxonomy of students enrolled in traditional versus remote offerings of the digital design course. Additionally, the frequency data for scores within Bloom’s taxonomy levels was analyzed to identify where the performance differences between the two offerings were situated.

Results

Student learning was assessed at the first five levels of Bloom’s taxonomy using the rubric in Table 1. Descriptive statistics for the overall scores (i.e., the sum of scores for the five levels of Bloom’s taxonomy) in traditional learning and remote learning settings are summarized in Table 2.

Table 2. Descriptive Statistics for Overall Scores

Statistic	Remote	Traditional
Mean	16.07	14.29
Median	16.00	14.00
Standard Deviation	2.73	3.32
Skew	-0.87(to the left)	-0.58 (to the left)
Kurtosis	0.58	-0.32

Both remote and traditional learning scores were only moderately and negatively skewed with values ranging between -1 and -0.5. Excess kurtosis values indicated that the distributions were approximately normal with excess kurtosis between -1 and +1 [22]. Therefore, subsequent statistical tests proceeded with assumptions of normality. Both the mean and median scores were higher in the remote offering than in the traditional offering. However, an independent samples t-test indicated that students performed better in remote (*M*=16.07, *SD*= 2.73) compared to traditional (*M*=14.29, *SD*=3.32) learning (*t* (82) = 2.65, *p-value* = 0.009). To understand more fully where these differences originated, additional comparisons between scores at each level of Bloom’s taxonomy were warranted.

Descriptive statistics for scores at each of the five levels of Bloom’s taxonomy are summarized in Table 3.   While at all levels, the mean score was higher in remote learning than in traditional learning, the difference was only significant at one of the five levels: *analyze*.

Table 3. Scores within levels of Bloom's Taxonomy

Level	Traditional (*N*=41)		Remote (*N*=41)		t-statistic	*p*-value
	Mean	SD	Mean	SD		
Remember	3.88	0.33	3.95	0.22	1.18	0.240
Understand	3.44	0.85	3.73	0.59	1.79	0.077
Apply	3.6	0.63	3.76	0.62	1.11	0.266`
Analyze	2.7	0.99	3.12	0.87	2.03	0.045*
Evaluate	1.95	0.92	2.38	0.98	1.55	0.120
Total	14.29	3.32	16.07	2.73	2.65	0.009**
* p<0.05; **p<0.01; ***p<0.001						

When using the remote lab setup, students' *analysis* scores were significantly higher than in the traditional laboratory ($t = 2.03$, $p = 0.045$). Scores in the *understand* category were higher in the remote laboratory than the traditional laboratory with emerging (marginal) significance ($t = 1.79$, $p = 0.077$). To get a better sense of where performance differences might be situated in *analysis* and *understand* categories, frequency data for the lab scores were examined (Table 4).

Table 4. Frequencies of Scores within levels of Bloom's Taxonomy

Frequency		**Score**				
		0	**1**	**2**	**3**	**4**
Traditional Offering $N=41$	Remember	0	0	0	5	36
	Understand	2	1	6	7	25
	Apply	1	0	3	10	27
	Analyze	1	4	15	10	11
	Evaluate	20	8	7	5	1
Remote Offering $N=41$	Remember	0	0	0	1	40
	Understand	0	0	3	5	33
	Apply	0	0	4	2	35
	Analyze	0	1	10	13	17
	Evaluate	15	6	7	10	3

At the *understand* level, two students scored a 0 at this level and one student scored a 1 in the traditional laboratory. In contrast, in the remote laboratory, the lowest score given in this category was a 3. This means that in the traditional laboratory, two students gave no block diagram or other indication of how their designs came to fruition, thereby earning a score of 0 in the *understand* category. Also, in the traditional laboratory, one student produced a working design but failed to break the design into modules, thus earning only a score of 1 at the *understand* level. No students in the remote laboratory did this. Thus, in the remote laboratory, all students successfully expressed an awareness of how to take a problem statement and divide it into pieces that can each be implemented independently while working toward a larger and functional system design. Additionally, at the *understand* level, 61% of students in the traditional laboratory earned an exemplary score (4) while 80% of students in the remote laboratory did so. An exemplary score of 4 in this category was indicated by providing an optimal design to the problem statement by showing the largest possible number of independent modules that successfully implement the whole design. Larger numbers of smaller modules usually lead to fewer states in FSM diagrams and in turn, improved timing performance.

At the *analyze* level, the same trend was observed. A total of five students at this level earned a score of 1 or 0 in the traditional laboratory, while only one student earned this score in remote learning. This indicates that in the traditional offering, 1 student did not attempt to simulate the design to show its functionality and therefore earned a 0 score, while 4 students made attempts at writing a testbench to simulate the design but the testbenches failed to come to fruition and thus earned a score of 1. On the other hand, in the remote laboratory, all students at a minimum had attempted simulating their design and no students earned a 0 score for this category, and only one student failed at simulating the design and thus earned a score of 1. As with the *understand* level, more students earned an exemplary score of 4 in remote learning (41%) than in traditional learning (27%). To earn an exemplary score for this category, students most often provided a fully functional simulation results for all the individual modules that constituted the design. This included the top-level module that combines all the independent modules and shows that the whole design was functional. Simulating the top-level module is a step that students often skip in lieu of testing the functionality of the design on the hardware without verifying it first in simulation.

Discussion

Students in the remote and traditional laboratory settings performed similarly at most levels of Bloom's taxonomy and differently only at the *analyze* level. For those levels in which significant differences did not emerge, the authors acknowledge that this result may be due to small sample sizes (*N*=41 in both remote and traditional laboratories) or it may reflect the lack of difference between the remote and traditional laboratory experience.

At the *remember* level, students in both traditional and remote learning earned comparable scores. This result was expected because all students come into the course prepared with the concepts learned from a common prerequisite class. Even though the degree to which a student remembers the prerequisite material well enough to hit the ground running varies with the time that has passed since taking the prerequisite, most students still remembered very well, with very few (6 of 82) scoring a 3 in this category and the remaining students earning an exemplary score of 4. This homogeneity in performance regardless of traditional or remote laboratory is likely a result of the fact that a vast majority of students enrolled in the junior level course associated with this study within 1-2 quarters of taking the prerequisite.

In contrast to the *remember* level of learning, differences in assessment scores were emerging at the *understand* level with two main themes. First, more students articulated their designs in their laboratory reports during the remote laboratory as compared to the traditional laboratory. And on the other end of the performance spectrum, more students earned perfect scores at the *understand* level in the remote offering of the course. The greater frequency of exemplary (i.e. perfect) scores in remote learning was linked to how well students showed the ability to divide a problem statement into necessary pieces or modules that could subsequently be implemented independently while working toward a larger and functional system design. In remote learning, 33 of 41 students were able to parse the Verilog design problem in this way while in traditional learning, only 25 of 41were able to do so. In remote learning, students may have realized that because they had limited access to the hardware, it was only prudent to spend more time in the design phase including in associated thought processes in order to increase their chances of successfully completing the laboratory. This aligns with findings by other researchers that correlated stressors with creativity [23] indicating that many students apply higher order thinking skills in times of stress. This result also adds to a body of research that has demonstrated that students perform at a higher level in remote lab environments [11].

The results of assessing the *apply* level in the traditional versus remote laboratory were similar to the *remember* level in that no significant differences emerged in student performance in the two offerings. This is an interesting result considering that students demonstrated differences in the frequency distribution of *understand* scores between remote and traditional laboratories. In the traditional laboratory, while three students received a 0 or a 1 score in *understand*, only one of those students received a score of 0 in the *apply* while the other 2 managed to submit a working design. This means that while some students could not articulate a working design, they could still build something that works. This result suggests two possibilities: (1) some students had limited ability or desire to write a complete lab report; or (2) the problem was not overly complex so that a brute force (i.e., single level, no modules) or guess-and-check design could be made to work. Writing abilities are certainly a concern with engineers in general [23] and many an engineering educator has seen an engineering student shortcut a more methodical design process when falling victim to procrastination or heavy workload.

Moving further up Bloom's taxonomy, significant differences between remote and traditional offering emerged once again at the *analyze* level associated with the laboratory in this study. Students in the remote offering of the course analyzed their design significantly better than students in the traditional offering. A likely possibility for this result is not the remote laboratory itself but accessibility to it. Since students had only two minutes to access the physical hardware via the remote link, they were more likely to more fully simulate their designs. This is good news considering that one of the learning goals of digital design course focused on developing the ability to use simulation as a crucial piece of more complex designs. If only via necessity and circumstance, students in the remote laboratory relied more heavily on simulation to prepare their code for testing rather than immediately jumping from design to hardware test. Time pressure stressors have also been correlated to greater creativity in the literature [24][25][26] which could have further triggered improvements in student performance when students were confined to the two-minute access intervals to the physical hardware.

In the last level of Bloom's taxonomy evaluated in this study, no significant differences emerged in the degree to which students were able to *evaluate* their designs. Most noteworthy in the *evaluate* level is the fact that twice as many students in remote learning (10 students) earned a score of 3 at this level compared to traditional learning (5 students). Thus, remote access to the FPGA set-up appears to have stimulated a greater reflection on design -- in whole or in part. Students were more likely to reflect on what they could have, should have, or might have done to improve their designs and also reflected on some of their choices they made in the design process. Such reflection is consistent with metacognitive awareness and strategizing which has been demonstrated as a key contributor to academic motivation and success [27].

Overall, results show that students performed better when presented with remote access to laboratory hardware than when having that hardware in hand. The remote lab provided a convenient and worry-free environment where students had access to the remote lab 24x7 and did not need to worry about maintaining the hardware or acquiring replacement for faulty components. However, they were also subject to a two-minute time limit in testing their code and demonstrating their designs. This combination of factors seems to have stimulated a better learning environment for students, a result that complements other studies which highlight the benefits of remote laboratories [11].

Limitations

The study offers a unique contribution to the body of literature in the use of remote laboratories in engineering and science by assessing learning outcomes of traditional and remote laboratories in digital design using an in-depth assessment process involving laboratory reports and Bloom's taxonomy. The study draws on a digital design course in electrical engineering at a single institution and therefore the generalizability to other engineering disciplines may be limited. The quantitative aspect of the study did not include the sixth level of Bloom's taxonomy due to the nature of the assignment. Additionally, the assessment was based on a single laboratory assignment that was the first in a series of assignments in the course.

Despite these limitations, the results of this study offer rich insight into rethinking engineering labs post COVID-19 and the potential of using remote labs as a cost-effective and sustainable approach that offers deeper and improved learning outcomes for popular digital design courses.

Implications

The study suggests that it is possible to transform engineering courses that require hands-on laboratories to a remote setting without compromising the quality of education that students receive and without affecting the expected learning outcomes. This solution can be extended to create open remote labs that are accessible by students beyond their enrollment in particular courses. In contrast, in traditional course offerings, students typically gain access to a physical lab kit for only a single term and must return the kit after the course is over or purchase their own kit if they want to work on side projects to develop their skills beyond the course work. In the context of this study, a physical lab kit includes expensive hardware that may not be affordable for all students beyond the course, creating equity issues. Using the remote lab provides an equitable solution that grants all students similar access to expensive hardware which may promote participation in extra-curricular activities such as design, build and test competitions. While this study focused on using the remote lab for a digital design course, similar approaches using rich assessment rubrics based on Bloom's taxonomy are applicable to electric circuits, and electric machines laboratories as well as labs outside of electrical and computer engineering.

Conclusion and Future Work

In this study, learning outcomes associated with using a remote lab environment for students in a digital circuits course during COVID-19 were studied. The study compared two modes of learning by evaluating one lab assignment that was given to students in a remote offering (in autumn 2020) and in a previous traditional offering (in winter 2020). Students using the remote lab environment scored higher overall and significantly higher within the *analyze* levels of Bloom's taxonomy, indicating that contrary to notions that the quality of higher education declined during COVID-19, student learning and performance actually improved in some areas. These results align with the findings of other studies that underscore the effectiveness and efficiency of remote laboratory environments. Our future effort will assess more assignments to provide a comprehensive statistical analysis of the two different learning environments. The promising results of using remote labs open the door for extending this approach to other engineering courses that focus on engineering design. The accessibility of the remote lab may offer an equitable solution that has the potential of increasing participation in extra-curricular activities among students in general and among under-represented students in particular, a research question that our future work will also focus on answering.

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