Innovation for Remote Teaching of Digital Logic Laboratory Courses

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Dr. Nazanin Mansouri is an assistant professor of Electrical Engineering at the University of Portland. She earned her Ph.D. in Computer Engineering in 2001 from the University of Cincinnati with a focus on formal verification of digital systems, where her research focused on developing methodologies for formal verification of digital hardware systems, and her B.S. in Electrical Engineering with a concentration in computer hardware design from Iran University of Science and Technology.

Dr. Mansouri has several years of experience working both in academia and industry. She has held positions as an assistant professor of Computer Engineering, and the director of the System-Level Integration research laboratory at Syracuse University, and as a System on Chip Design engineer working on power management at Intel Corporation.

Dr. Mansouri's research interests are in the broad area of digital design and include the development of theory, methodologies, and tools for the design of high-performance Systems on Chip (SOCs), VLSI Design and CAD, applications of machine learning to design automation, high-level design and synthesis techniques for low power, embedded systems and functional and formal verification. She has published several papers in top-tier conferences and journals in her field and has presented her research at numerous international conferences.

In addition to her research, Dr. Mansouri is passionate about teaching and mentoring the next generation of computer and electrical engineers. She has designed and taught many courses in computer engineering, has supervised several undergraduate and graduate research projects, and served as the thesis advisor to several M.S. and Ph.D. students. Dr. Mansouri was the recipient of the ”Excellence in Graduate Education” from Syracuse University in 2008.

In her free time, Dr. Mansouri enjoys exploring nature, photography, and writing short stories. She is also an advocate for diversity and inclusion in STEM fields.

Dr. Mansouri is an accomplished engineer and a passionate educator with a strong dedication to supporting and mentoring all her students, particularly women and other under-represented and minority groups. She encourages all her students to push beyond their limits.

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Abstract

This paper presents how the serious challenges in teaching laboratory courses during the COVID-19 pandemic and transition to an online mode of instruction were overcome by design of an innovative test-board that served as the needed infrastructure for teaching a "remote" or "personal" [1] laboratory course. This solution not only provided the students with equitable infrastructure for doing all the required projects and hands-on experiments remotely but also could be used as a learning opportunity to provide students with more insight into the setup, design, functionality, and purpose of lab equipment. While in typical academic years and in the normal (in-person) mode of operation, the sophomore students in this course learned to use the laboratory equipment for doing projects and lab experiments, in this remote course students additionally learned how these equipment are designed and built through building one – the test-board – as one of their first projects. This test board served as key component in making hands-on experiments of the course in a remote setting possible.

The remote experiments, testing, and evaluations were done following a formal and methodic approach, instead of ad hoc practices. In general, this approach led to effective and efficient experiments, and also served as a model to think creatively and methodically for solving engineering problems and planning prototype development. Overall, the design and use of the test board proved instrumental in the successful remote delivery of our digital laboratory course such that all the previous in person course experiments were completed in the online course without any limitations and the course's educational outcomes were met. The assessment of the identified ABET performance indicators at the end of the semester were above the acceptable threshold and comparable with the in-person course. This experience demonstrates that through innovation, some of the engineering laboratory courses can be taught remotely without sacrificing any experiments.

1. Introduction

One of the most meaningful measures of an engineering program is for its graduates to be able to perform from the first day on the job. It is only through a fine interplay of the theory and practice that such an outcome can be achieved. Hence, it is imperative that when developing courses and curricula, we keep a theory to practice outcome in mind. What distinguishes the new graduates in engineering disciplines is not solely strong theoretical foundations, but more importantly their ability to deliver products. As we have become more dependent on remote learning and online instruction, when evaluating the quality of the engineering courses, it is crucial to keep the acquired practical skills to as high an esteem as the acquired theoretical knowledge.

COVID-19 pandemic presented many challenges to educators who had to transition to an online course delivery mode. Teaching laboratory courses and courses requiring hands on experiments remotely had unique and additional challenges as students did not have access to laboratory tools and equipment. To avoid compromising the quality of these courses and meet their educational outcomes, it was crucial that students could benefit from the same experiences and conduct the same experiments in a remote setting as in the standard in-person courses. Engineering educators found different solutions for teaching laboratory courses, based on different objectives.

This paper, focuses on this problem, and through a case study provides an example of a successful offering of a laboratory course that is traditionally delivered in person and relies on specialized hardware. We present the case of a digital logic laboratory course that due to pandemic unavoidably transitioned to remote delivery. We discuss and demonstrate how an innovative solution focused on the quality, educational outcomes (theory as well as practice) and equity, lead to a richer learning experience than the conventional in-person course. Our solution was based on several objectives some of which included (1) offer a "*remote or personal laboratory*" that comprised of both simulation and hands-on experiments, and not a *"virtual laboratory"* solution that is exclusively based on simulation; (2) provide the remote learner student with the opportunity to do the exact same set of experiments they would have done in the in-person laboratory course; (3) teach experiments methodically and by providing sufficient guidelines to students, rather than relying on them to find ad hoc solutions and do patchy work; (4) Provide live (synchronous) guidance and support to students, rather than leaving them on their own; (5) avoid acquiring costly specialized software and tools and keep a reasonable budget as close as possible to the cost of the in-person laboratory. We achieved this by design of a test-board that was the key element in achieving all these goals.

This experience proved that with creativity and advanced planning, some of the laboratory courses can be delivered on an online platform without compromising the quality, outcomes or equity. Throughout the paper, we demonstrate that engineering educators should shift from the mindset of making the existing solutions fit our ever-evolving teaching platforms, and rely on creativity and innovation to find new paradigms that target the needs of the new delivery mediums. In our case innovation in design of a test-board was the key in achieving our goals rather than settling for a virtual lab based on simulation and consequently sacrificing the hands-on experiments. In what follows we present the traditional laboratory course setup and delivery, then introduce our test-board and discuss how it was used as the main infrastructure of a remote/personal laboratory and enabled us to recreate the laboratory experience in individual remote setting of students. We will also discuss the advantages of this lab over some of the other solutions.

2. Related Work

The impact of the COVID-19 pandemic on engineering higher education was discussed in [2]. Depending on their objectives and constraints, engineering educators had different solutions for teaching laboratory courses during the pandemic. A first group dealt with teaching engineering laboratory courses during the pandemic by reducing the laboratory capacities and modifying the teamwork requirements, and providing conditional access to the lab [3]. In a similar hybrid approach, the authors offered an optional access to the laboratory in an online course, while reporting that all students opted for conducting the experiments in the lab rather than in a remote setting [4]. However, such an option was not available in many states and may not always be available in other circumstances. Our approach differs from both these practices, as we consider remote learning of a laboratory course a situation where students are geographically spread out and do not have access to any lab.

Other groups in academia found the solution to online transition in offering a modified experience, where hands-on experiences are mostly eliminated and experiments are conducted exclusively through simulation [5]. They often use *virtual labs* that use computer simulations rather than *remote or personal labs* that require portable devices. Our approach differs from these groups, as it was a main goal to focus on hands on experiments, rather than simulation-only virtual labs. While such solutions are valuable, they put the student in an online laboratory course at a disadvantage compared to the student who is physically present in the lab. In such approaches, the focus in online instruction is not on equity in learning opportunities, but more on engagement and class environment simulation that can also be achieved as a by-product if the remote laboratory courses are planned well.

A different group of educators for some topics such as control systems or IoTs, adopted a superior hybrid virtual lab solution, where the laboratory equipment where remotely controlled by students [6]. Such approaches do not apply to a digital logic laboratory.

A final group of educators opted for a remote or personal laboratory solution. In sharing experiences with the few colleagues in Electrical or Computer Engineering within or outside our home institution who had opted for a remote or personal lab, it was apparent that their focus was more on planning the physical parts and kits and less on the methods of delivery. Students worked mostly asynchronously, and were on their own to navigate their circuit design journeys and had to overcome road-blocks independently through ad-hoc methods. In contrast, significant effort is made in this work to enable students conduct experiments methodically and effectively and support them in the class sessions as it would have been done in an actual laboratory. This was all possible due to the design and use of our test-board. The test-board allows to build, test and debug the circuits methodically and eliminates repetitive work. For these reasons, it reduces both the possibility and frequency of errors, and minimizes the debug effort and the student frustration that results. It allows effective remote demonstration of circuit functionality or circuit debug. Had we provided the exact same hardware kits to students without building the test-board, many of these benefits would have not been possible, and the time and experiment overhead would have been prohibitive to complete all the experiments.

As an example, the first and most common circuit failure is in power delivery (particularly for a novice student). When students connect the power to the board, they don't know if the board is powered or not (in case of a disconnect or incorrect connections). Such a problem is very quickly and easily detected and corrected using our test-board with a power-on indicator

(See Figure 3). In ad-hoc methods used in remote labs, student spends a great deal of time to debug this simple failure as they cannot easily distinguish this error from the errors in the main circuit. As another example, the test-board makes use of switches that supply the logic '1' or '0' values to the circuit inputs, and pair of red-blue logic indicators that depending on the lighting of the LED pair, determine the output logic value to be '0', '1' or "X"/"Z". It is very easy to accurately apply the values to the inputs and read the values at the outputs. The good practice of assigning inputs and outputs an order alphabetically or numerically, makes it easy to visually follow the function of the circuit in demos or debugs. A beginner student can confidently go through their truth table, and without confusion apply all the combinations of 3 input variables using 3 switches to the circuit, and observe the values of the 3 outputs on 3 pairs of logic indicators in very little time. They start from one combination and with sliding the switches, the next combination is applied (See Figure 9). This also helps the professor or TA to easily verify the correctness of the circuits (exhaustively or randomly), or help in debug when necessary. In ad-hoc methods, student has access to all the same parts, they may choose to use the sliding switches for inputs and logic indicators for output, however, they have to repeat the process for each circuit. Moreover, the test circuitry and main circuit are intertwined and in case of errors, the possibility of errors in both circuits exists, while our test circuitry is built, tested and debugged once and used throughout the semester, and the possibility of errors in the test circuit is small. In effect we isolated the errors in test-circuit from the errors in main circuit. In addition, since the circuits in ad-hoc solutions are not built uniformly and are not identical, remote demonstrations and more importantly remote debug are very hard. In ad-hoc approaches it is also very hard for students to share their work and make comparisons. Additional benefits of our test-board are explained in the following sections.

3. The Laboratory Course Structure and Background

Our "Digital Logic Laboratory" course is taught in the Spring (second) semester of the sophomore year, paired with a second more advanced course in logic design "Digital System Design". In this laboratory course, students learn how to hierarchically design, simulate and implement digital systems using small-scale (SSI) and medium-scale (MSI) integrated circuits as physical components. The focus of the Digital Systems Design course (The co-req course), on the other hand, is advanced design concepts at higher levels of abstraction, and involves projects that introduce students to hardware description languages (structural Verilog) and design synthesis and prototyping using FPGAs. The lab focuses on the lower-levels of abstraction, and complements the course by concentrating on building, testing and debugging prototype physical circuits from basic parts. Students gain valuable hands-on experience.

Students begin from simple experiments that focus on functionality of primary gates, then basic components such as encoder/decoder and multiplexers and move to incrementally more complicated and interesting experiments. They learn how to implement functions using multiplexers and decoders. They design, implement and test various combinational and sequential circuits such as full-adders, majority function, a basic elevator or counters. They also experiment with memory components, for example, by extracting the data stored in a flash-memory and using this data in another logic experiment.

The lab is a one-credit hour required course for our program that meets 3 hours per week. It is a prerequisite course to another required junior-level course “Embedded Systems”. There is a maximum capacity of 14 students and there is a teaching assistant from the upper-class population for each section. Students ideally work in teams of two.

The class begins with a short lecture that guides students through the specifics of the day’s experiments followed by Q & A.

A week in advance of each class, students are provided with the lab handout that outlines the problems to work on. They are expected to come to the lab prepared having done the “pre-lab” theoretical work that shows their designs based on the given specifications, the logic circuit diagrams, and the expected outcomes of the experiments. The outcomes are defined as the expected outputs in response to a set of inputs, documented using truth-tables, Karnaugh maps, state-transition tables/diagrams, or similar methods. For a short interval following the lecture, students’ theoretical work are verified by the instructor or the teaching assistant before they can proceed to the next step.

Students then use a simulator with a schematic capture entry to draw and simulate their gate-level circuits. They are expected to compare the observed simulation results with the expected results they have previously computed, and in case of inconsistencies debug their circuits, make corrections, and repeat the process. Once simulation results consistent with the expected results are observed, and the functionality of the circuit implementation is verified through simulation, students implement the circuits using physical parts and see the functionality of the actual circuit.

Students use the ICs, parts, and tools available in the laboratory to build their circuits on the electronic training-boards in the lab. The electronic training-boards are the main infrastructure we rely on for implementing the circuits in this lab. These units are designed with broad functionality for building and testing digital and analog electronic or electric circuits and prototypes. Depending on the specific experiment or the particular skills of the group of students, the test and debug stage can be fast and simple or lengthy and complex.

The physical circuits that students build may not work as expected for various reasons. In such cases, a team may spend a considerable amount of their time in the lab to debug their circuits and identify the source of the problem. They generally follow the guidelines provided to them and work together to locate the problem. If they are not successful, they seek help from their instructor or their teaching assistant for debug and troubleshooting. Generally, every group has some faulty circuits during the semester and needs to debug and correct their circuits. Students learn that debug is a critical part of the design process, and as the complexity of the designs increases, the majority of the time of even the best designers is spent on debug.

Our EE program has recently gone through the re-accreditation process. One of the strengths of the program is students' hands on skills. In our program, the capstone project is a two-semester course, and students are required to develop a working system as a prototype in teams. Many capstone projects are sponsored by local industry. Student teams design and build circuits with well-defined practical applications. For example, several capstone projects were sponsored as real devices to be used to aid the disabled individuals, particularly disabled children. As such, our students are required to build systems consisting of hardware (analog and digital) and software and having many different components and physical parts (power supplies, LED matrices, keyboards, specialty switches, sensors, …). All the capstone projects unavoidably have some digital parts. The digital logic laboratory course teaches them engineering problem-solving skills. The teams need to learn from data-sheets and integrate various modules and parts, and create working interfaces. This often requires significant skills in building circuits and debugging them. This laboratory course serves as the foundation course to teach students the basic knowledge and skills in planning, design, simulation, implementation, verification, testing and debugging of their first circuit prototypes and they gain experience by methodically putting them to use. They build on the knowledge and skills learned here in the more advanced courses that follow. This lab plays a significant role in preparing students for such upper-level courses with more practical projects such as courses on "Embedded Systems", "Testing of Digital Circuits", but most importantly, students take a great deal of experience from the lab and apply it to their senior capstone projects, as well as, in their future careers.

3.1 Course Content and Outcomes

The following lists some of the educational goals and the students' acquired knowledge and skills upon completion of our digital logic laboratory course:

- Design and implementation of logic circuits: theory, simulation, physical circuit
- Introduction to TTL Gates
- Design with small-scale integration (SSI) and medium-scale integration (MSI) components
- How to read data-sheets to learn about the functionality of an integrated circuit
- How to verify the correctness of your design
- Logical errors (e.g. swapping pins) and physical errors (e.g. faulty tie-point, defective ICs)
- What is a good and clean circuit
- Good practices & not so good practices in building a circuit
- Good practices & not so good practices in debug (pinpointing the source of errors)
- Isolating errors in debug by traversing the circuit module by module from outputs to the inputs (or vice versa)
- How to plan to develop a prototype from start to finish
- How to work in teams
- How to write professional reports
- How to present your design idea and demonstrate its functionality

While we primarily use TTL gates (ICs) in our experiments, the practices learned in this laboratory course are not limited and can be applied to other situations. Students expand their experiences in more advanced courses such as our Embedded Systems course, when they learn to work and interface with a PIC microcontroller.

3.2 Laboratory setup

3.2.1 Hardware (online vs in-person)

The main hardware infrastructure used in this laboratory is the PB-503 Analog/Digital Design Trainer Proto-Board [7]. This unit is very critical in performing the experiments in the lab throughout the semester. The trainer consists of a large breadboard (3 breadboards are connected to provide enough room for building circuits) and a variety of logic control sections. The control sections are located around the breadboard. These control sections perform a variety of useful logic functions. These functions include (starting from the upper left corner moving ccw):

1. Function Generator: This module can create various outputs with adjustable waveform (sine, triangular, and square), frequency, amplitude, and CMOS vs TTL outputs.

2. Debounced Push-Buttons: Two debounced push-buttons each with 8 tie points of two different types (NC or normally closed and NO or normally open). These push-buttons provide a conditional connection to the ground.

3. Bayonet Neill Concelman (BNC) Connectors: Two BNC connectors that allow connection of the trainer unit to oscilloscopes or other test equipment without using clip leads.

4. Logic Switches S1 to S8: This section consists of eight sliding type logic switches. When a logic switch is in its up position, it is placing its tie points on the connector to logic 1. The down position of a logic switch sets its tie points to logic 0.

5. 10k/1K Potentiometer: The unit has two POTs, one is 10k and the other is 1k.

6. Single Pole Double Throw Switches S9, S10: Two SPDT switches allow to set conditional connections between the middle and the top or the bottom leads.
7. Speaker: Each of the two speaker leads has four tie points on the connector.

8. Logic Indicators: This section is used for reading the value of a logic signal. It contains some control switches, 8 input connector tie-points, and eight green-red LED pairs. There are two options for +5/+V (a variable positive voltage) inputs. Another adjustable option is TTL/CMOS. The input to each set of tie-points is usually the output of a logic gate or other signal that needs to be read and the output is the corresponding pair of green-red LEDs. The Red-Green LED pairs show the voltage values at the connector. The green LED is lit when the input is logic 0 and the red LED is lit when the input is logic 1. If the input voltage is neither logic 1 nor logic 0, neither LED will light.

9. Breadboards: This section is used for building and testing the circuits in various experiments.

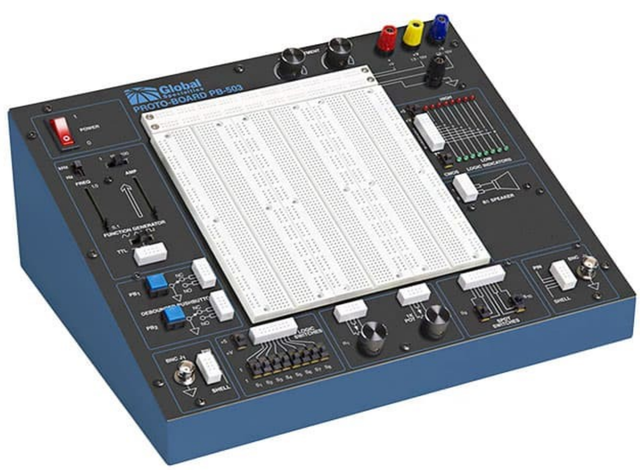

Figure 1: PB-503 Analog/Digital Design Trainer Proto-Board

3.2.2 Software

The software used during the simulation of the circuits, and prior to building them with physical parts is B2 Spice A/D software [8] that allows to do realistic simulations with virtual version of ICs and parts that are used in building the real circuits. The graphic schematic capture of this tool allows to draw and simulate a circuit model in a fraction of the time required for building the actual circuit. The exact instances of IC units, the pin numbers, and the connections of the circuit to be built can be precisely modeled. Simulation allows the functionality of the circuit to be verified and for the circuit model to be debugged and corrected if needed in a very short amount of time. Once it is established that the circuit model is functionally correct, building of the real circuit can begin.

3.2.3 Parts

For building their logic circuits, students mostly use various TTL Integrated circuits and basic components such as resistors and LEDs. They use the basic primary gates (7400 series multi-input NAND, NOR, NOT, AND, OR, XOR, …), flip-flops (JK-FF and D-FF), Multiplexers, Decoders, as well as components such as flash memories. They are also provided with basic tools. They build their circuits using the required ICs on the trainer proto-board, then generally test and debug them (as far as possible exhaustively and otherwise with good case coverage) until the expected behavior is observed.

3.3 Experiments (Support and Interaction)

The lab activities consider 3 checkpoints for each experiment:

1. Verification of the pre-lab theoretical work, and the logic circuit drawn on the paper. This shows that the pencil and paper design of each circuit is correct, and defines the expected behavior of the final circuit implementations.
2. Verification of the simulation results demonstrating that the observed behavior of the simulated circuit is consistent with the expected behavior, and debug and correction of the circuit model in case of inconsistency.
3. Verification of the behavior of the final circuit implementation, by comparing the observed behavior with the expected behavior, and debug and correction of the actual circuit in case of inconsistency.

At each checkpoint. the work of each team is verified by the instructor or their teaching assistant. Also, the instructor or their teaching assistant provide guidance on how to approach a specific debug problem and support students during hard debugs when root-causing and locating the error in the circuit is not trivial. Generally, debug is the most time-consuming part of experiments, and is when students rely on their professor and teaching assistant the most. When the lab is conducted in person, the activities proceed smoothly and experiments are completed within class time. Occasionally, due to incomplete pre-lab work or a hard debug students may need to work beyond this time-frame.

4. Transition to Remote Learning

In the Spring semester 2020, just upon return from the midterm break, the pandemic was declared, and we had to move to online instruction unexpectedly. Before the university shut down, the faculty had a couple of days to prepare for the transition to online instruction which did not permit much planning. This particularly posed a problem for courses relying on hands-on work and laboratory courses such as this one. For this course, the instructor distributed some of the available physical parts that students needed for the experiments. However, there were not enough breadboards, ICs and parts available to distribute to the individual students in all the sections of the course. Students were encouraged to take some basic tools and parts available in laboratory home with them, but school could not supply the rest, and ordering parts and shipping kits to students for the rest of the semester could not be done in a reasonable time. As a result, the physical experiments had to be dropped and we focused on students' theoretical work and simulation exercises. However, even that was not always possible, as some of the experiments could not be done through simulation. As an example, in one of the lab activities students learn how to read/write from/to memory modules. They are provided with a flash memory, and are required to apply appropriate signals to read a subset of words and extract a function that was coded in the contents. In the absence of a physical flash memory unit, this experiment had to be dropped.

4.1 Simulation vs Prototyping

As we continued with remote instruction into the next academic year, some of the challenges of online instruction were met with better planning. In Fall 2020, when planning the Spring 2021 laboratory course, the author pondered on the question: "what if we can use the online instruction as an opportunity for doing more autonomous hands-on learning instead of settling for degraded expectations (simulation only) and a less than ideal student experience?" This challenge led to an online version of the course, that provided students not only with the same level of hands-on experiments as the in-person version of the course but additionally with the unique experience of developing a test environment and infrastructure that they could use as a model in their future prototype development practices. This, however, required much creativity, advance planning, preparation, and proof of concept development on the part of the instructor.

5. Planning

An online digital logic laboratory course could not be successful by merely putting together a good collection of parts/ICs in a kit and relying on students to use ad-hoc methods to build and more importantly test and debug the circuits. Identifying a complete set of physical parts and suitable software is only a small part of what is needed. Upon careful reflection, the following objectives deemed critical if the course were to be successful:

- A methodic approach for implementing and testing circuits could be developed.
- An infrastructure for building and testing the circuits similar to what is available in the lab could be available to students in their remote setting.
- Students could finish the experiments within a reasonable time. A careful study showed that this required to:
  - Use a methodic approach to implementing and testing circuits

- Identify all the required parts and preparing the kits in advance
- Set up numerous checkpoints and define clear timelines
- Eliminate repetitive work
- Reduce the possibility of errors
- Enable autonomous debug
- Provide the facility for students to get effective help from their instructor, their TA, and their peers remotely
- Define a clear and concise method for students to demo the functionality of their circuits
- Effectively deliver debug and general support in the remote setting
  The key that proved crucial for achieving this particular goal was for all students to have the exact same set-up of their test-board.

What proved pivotal in achieving these objectives was the design of a test-board to be built by students and used throughout the semester as the lab infrastructure (Figure 2).

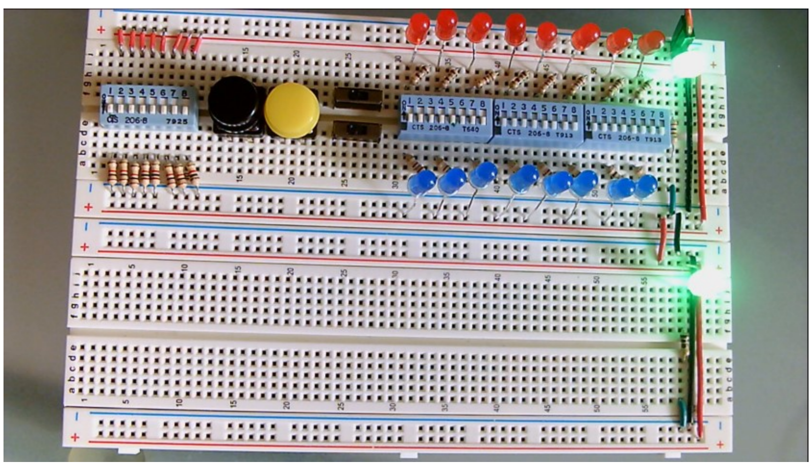

Figure 2: Test Board and Design Board Integration

5.1 Board Design

The key element in the successful remote delivery of the laboratory course online is the test-board. The test-board was designed as a substitute to the Proto-Board units available in the laboratory, with the intent to streamline the functionality to what was critical for the experiments in the course. We considered the following features/modules/sections necessary:

1. Breadboards (minimum 2)

   The test-board consists of a minimum of 2 breadboards that snap together. We need one “test” breadboard that is exclusively used for support/test purposes during our experiments, and at least one other “design” breadboard that is used for building the main circuits. If more space is needed, more design breadboards can be added. Figure 2 shows the integrated test-board. In this figure, the top board is used for support/testing, and the lower unpopulated board is used for building the main circuit.

2. Power-on indicator

This simple feature targets the most common debug problem: the board does not receive power and the circuit appears dead. This is particularly hard to detect when troubleshooting the circuits that are built and tested using ad hoc methods. This most frequently encountered problem in circuits can happen because of forgotten connections, loose connections, or swapping the power lines. Students are instructed to connect the bus strips and then add two green LEDs as power-on indicators: one for the support/test board and one for the design board. The power-on indicator visually helps with the immediate detection of the problem.

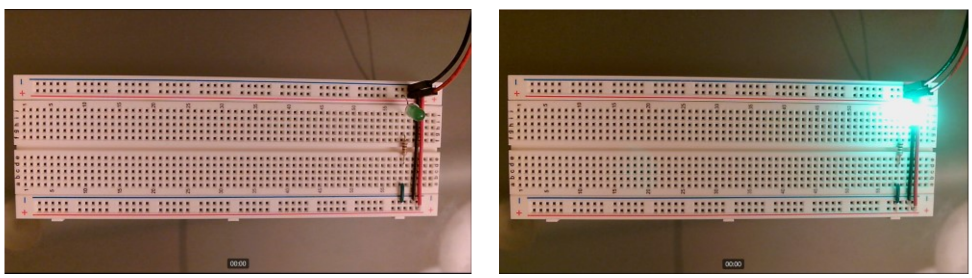

Figure 3: Addition of Power-On Indicator LEDs

3. Function generator

We used Analog Discovery 2 (AD2) [9] units as our function generator to supply power to our boards. The “Supplies Mode” is set to the positive supply voltage of 5V and then AD2’s Positive Supply Channel jumpers are connected to the bus strip of the test-board. The AD2 units were readily available to students in our program, as these units were ordered and used in the pre-requisite course Electric Circuits Lab. These units are loaned to students and are returned to school upon completion of the course. In the absence of AD2 units, and in cases where the cost is prohibitive, interested individuals can use 9V batteries together with an inexpensive voltage regulator to create a 5V supply for their boards.

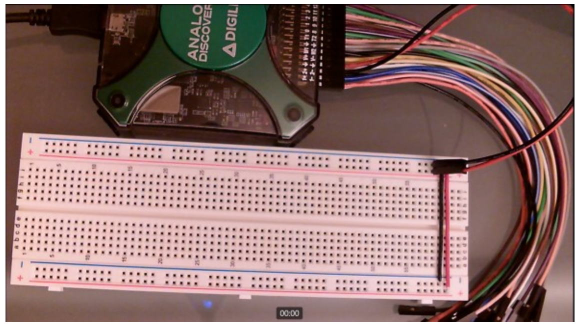

Figure 4 Analog Discovery 2 100MS/s USB Oscilloscope, Logic Analyzer and Variable Power Supply

4. Logic indicator section with 8 LED pairs LD1 to LD8:

   This section consists of eight pairs of red-blue LEDs. The LEDs are used for reading the logic value of the signal at the tie-point (i.e. we can read the logic at any point in the circuits by connecting them to the input tie-point of one of the LED pairs).

   a. Parts – For building this partition 8 blue LEDs, 8 red LEDs, 3 × 8-position DIP switches, and 16 resistors were used.

   b. Function – The Red-Blue LED pairs show the voltage values at the connector. The Blue LED is lit when the input is logic ‘0’ and the Red LED is lit when the input is logic ‘1’. If the input voltage is ‘X’ or ‘Z’, both or neither LED may light.

   c. Circuit Assembly – Instructions for assembling the circuit with the exact row/column location of each pin are provided. All students use strict guidelines and precise locations for assembling this section like the rest of the support/test board.

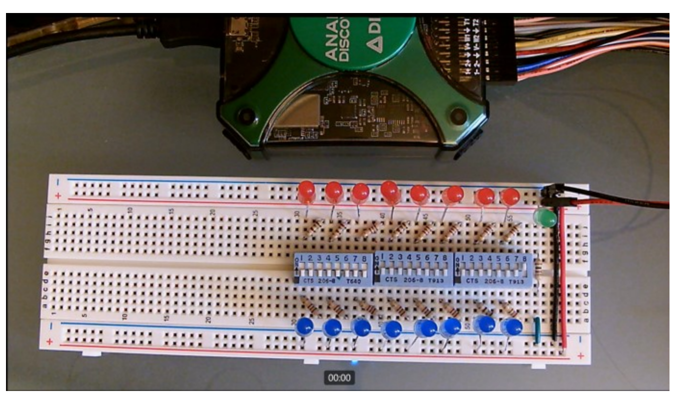

Figure 5: Adding the Logic indicator section with 8 LED pairs

5. Two Debounced Normally-Open (NC) Push-Buttons

   We can wire these switches such that one can make a conditional connection to Vcc and the other a conditional connection to GND. We can also use these switches to make conditional connections between other points in the circuit. Students verify the connection of the buttons and learn about their functionality and usage after adding the logic indicators.

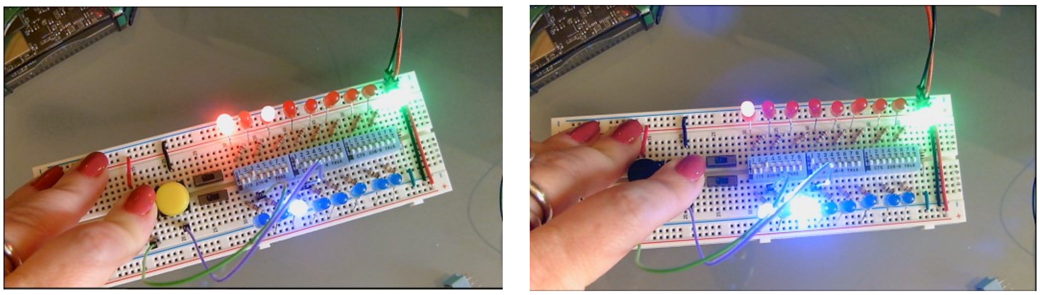

Figure 6 Addition of Debounced Push-Buttons

6. Logic Switches S1 to S8:

   This section consists of eight sliding type logic switches. When a logic switch is in its up position, it is placing its tie points on the connector to logic 1. The down position of a logic switch sets its tie points to logic 0. These switches are used to generate the logic ‘1’ and ‘0’ inputs to the circuits during the experiments.

   An 8-position DIP switch and 8 resistors are used to build this section. Instructions are provided to students on how to add the resistors and make connections to Vcc and Ground to attain the desired functionality.

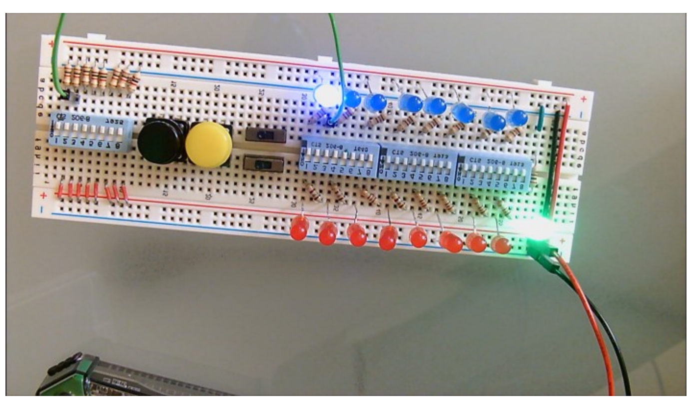

Figure 7 Testing the input logic generation through Logic Switches

7. A set of resistors:

   While the Design Trainer Proto-Board available in our digital laboratory includes a potentiometer, due to cost restrictions we provided students with all the resistors they might have needed in their experiments.

Figure 2 shows the completed test-board with all the required functionality after various sections and modules have been added. Figure 8 shows sample boards of some students in the course. As can be seen, these identical board setups make it very easy for all the students to have access to a basic infrastructure for doing successful hands-on experiments. They can use many creative ways in design and implementation of their logic circuits, and at the same time have a uniform way of demonstrating the functionality of their circuits.

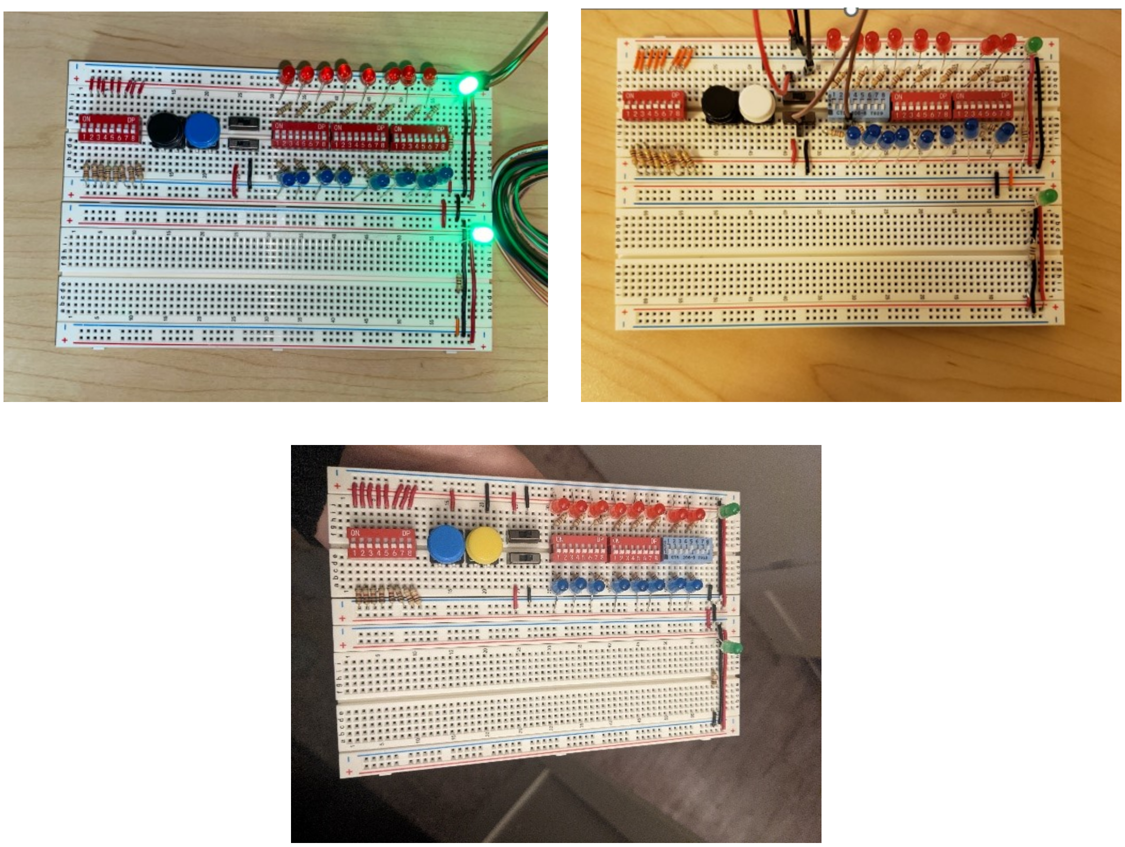

Figure 8: Sample test-boards built by 3 students in the course

There are many advantages to building this test-board with its precise specification in comparison to ad-hoc methods that use the switches, LEDs, resistors, and other parts on demand for each experiment. In ad hoc methods, for each experiment, there is a hidden overhead for building and testing the support/test circuitry and dealing with debug and a great deal of repetitive work. However, in our method, there is a one-time upfront overhead. Our test-board is more generic, has components and sections that are beyond the need of any single experiment in the course but can be used in all. It is built only once and used throughout the semester and beyond (for as many experiments as needed). Students spend two lab sessions to build and fully test it. Our method is, therefore, significantly faster and more efficient. It is concise and methodic, teaches good design practices to students, and reduces errors throughout the process. The following are some of the benefits of the test-board on its own or in comparison to ad-hoc methods of building and testing circuits:

- Localizing the troubleshooting by isolating, to a great extent, the errors in the test circuitry from the errors in the main circuit – Using ad hoc methods, in each new lab experiment, a new and different set of support/test circuitry is required and the additional test logic is unique to the needs of the particular experiment. However, the new test circuitry has the same likelihood of having errors (in its logic and wiring) as the main circuit. In case of circuit malfunction, it is hard to know if the errors are in the main circuit or in how the circuit is being tested, i.e. in support/test circuitry. Hence, using our method has a great advantage when debug and troubleshooting in locating the errors.

- Significantly reduce the possibility of errors in the support/test circuitry as this logic is generic; it is built and tested methodically (thoroughly tested once and requires simple maintenance checks for each experiment) and we have a good degree of confidence in its correct operation – Hence, in our method, the design malfunction is mostly due to errors in the main circuit. In ad hoc methods, the support/test circuitry is specific to each particular experiment and needs to be tested together with the main circuit. Therefore, in our method, the design under test (DUT) is smaller compared to the ad-hoc methods. Since larger circuits are more prone to errors and harder to debug [10], our method leads to an overall error reduction in final circuits. In addition, as experiments and building circuits are more structured and methodical, the circuits are cleaner and developed with more accuracy. As a result, the likelihood of the first-time correct designs is higher compared with ad hoc methods.

- Significantly reduce the troubleshooting and debug time – For the reasons mentioned above, even when errors are made in building the circuits, they are faster to locate. As test and debug are done in a modular fashion, with support/test circuit being tested separately from the main circuit, the testing and validation of the circuits in our method are much more efficient and significantly faster.

- Sharing of experiences and getting support becomes more viable – It is needless to say that interaction and learning from peers become much harder in a remote setting than in a lab. An engineering laboratory has the inherent benefit of encouraging student interaction and creating enthusiasm about common experiences. Students learn from others' mistakes and share their experiences collectively. They can offer their peers support during a hard debug. They can see one another's circuits. They develop their sense of "good practices" and "not good practices" together. One of the challenges of remote laboratory courses for an instructor is how to promote these interactions in an online setting.

In our course, the test-board had a very positive impact in encouraging these interactions. The board had a very precise implementation, and the professor, the teaching assistant, and all students looked at identical boards with the exact same set up (See Figure 8). The instructor's insightful decision to require identical setup and interconnections on test boards (down to the pins/tie-points) reaped its benefits on this point. The remote trouble-shooting and support (from the instructor and TA to student, as well as, from peer to peer) became feasible. It became possible to demonstrate on the board for instruction and students could follow and reproduce the steps, provided pin-tie point addressing, allowed visual inspection of the circuits and connections – even while using standard cameras on students' mobile devices - or provide instructions remotely. Basic errors in wiring could be immediately detected remotely by visual inspection. Students could share their experiences with their peers and demonstrate their final circuit functionality for evaluation to their professor. They could see and compare their work. Team work was facilitated. These could have not been possible through ad hoc methods as is it hard if not impossible to understand and follow different logic of individual student circuits remotely, and harder to do successful debug.

Figure 9 shows snapshots of a student demonstrating the functionality of their circuit. This is a combinational circuit with 3 inputs and 3 outputs, and student shows their circuit functions correctly for all possible input combinations. It is easy to follow the position of the input switches and the value read by LED indicator pairs corresponding to each output. For careful debug it is practical for students to share a photo of their circuit and get help. It is easy for students to go through the input combinations together and visually compare the output values in their circuits. Such exercises were next to impossible using ad-hoc methods.

- Increased productivity and equitable instruction – This board made the online lab experiments more efficient and allowed students to work and complete the exact same experiments that were done in a standard in-person laboratory course. No compromises were made in the quality of the remote course compared to the in-person version.

- More insight into how the lab equipment is designed – While students learn how to use the lab equipment for their experiments in a standard in-person version of the course, the experiences of learning about the design and building of the test-board provided students with a unique opportunity to additionally gain a better understanding of how the lab equipment are designed.

- Great project development skills and increased autonomy and confidence – Students who completed the laboratory course remotely were challenged more, and hence gained superior skills in autonomous problem solving, circuit implementation and debug. The work in this lab set the foundation for many more challenging projects to come. These skills helped them in doing more advanced project work in their upper-division courses.

- Exemplary Circuits – As a side benefit, the precise initial work of building the support/test-board encouraged this generation of students more than ever in carefully floor-planning and continuously striving to improving the routing and wiring of their circuits. This class had some of the cleanest and best planned circuits in a few generations.

- Owning a test-board – Each student in the course implemented their individual board to keep for their personal experiments for the remainder of their studies and beyond. In some cases, the board was the starting point for more advanced design work by students during their leisure time.

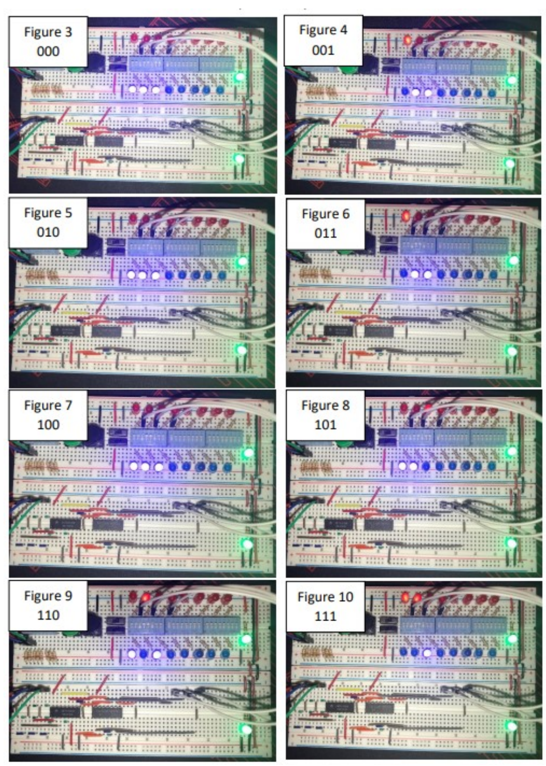

Figure 9: Snapshots of student demonstrating their circuit functionality for all the combinations of 3 input values

5.2 Kit Orders

During the planning phase for the course, several categories of components were identified to be included in the kits that would be shipped to students:

- The components and parts needed for building the support/test board (Breadboards, LEDs, various switches (sliding, SPDT, 8-position DIP, push button), resistors
- Electronic/Electric components for building main circuits - see section 3.2.3 (ICs, resistors, LEDs, …)
- Generic components
  (Wire-kits, jumpers, alligator clips, …)
- Tools
  (Pliers, wire strippers, screwdrivers, …)
- Analog Discovery 2 (AD2)

The course professor (the author) calculated the quantities based on the maximum needed in any one experiment and then allowed spare units of most electronic and generic parts. Based on this list kits for students were assembled. The kits were meant for students to keep, except for AD2 units due to their cost and flash memories due to the overhead of their programming by technicians, being on loan to students for the duration of the course.

Costs:

Including the flash memories and a good number of spare parts, we were under an $80 budget for each student kit, and less than $20 of this amount was spent on the components for the test-board. This shows that teaching digital logic courses with a complete set of experiments can be very inexpensive and effectively done with basic components and good advanced planning.

The orders for the components were sent out before the end of the Fall semester, and our school technicians assembled and shipped the kits to students in January.

5.3 Preparing Graphic Tutorials

The course professor prepared very detailed written tutorials ***("Building a Fixed Test Board Tutorial")*** with abundant images and step by step instructions to guide students through incrementally building and testing the board. The tutorials are very descriptive and provide strict and precise specifications for the board assembly. Each component has a precise location in the board down to the address of each pin and tie point connection. This was necessary to allow for productive independent work and at the same time for successful remote collaboration, demonstration, and debug. Figure 10 shows a snippet of the tutorial that provides instructions on how to add and test the function of the SPDT switches. As can be seen, the images in the tutorial demonstrate how the resulting circuit should look after each addition and also visually help on how to set up the interconnections for doing the experiment.

5. **SPDT Switches**

Two single-pole double-throw switches are provided to you in your kit that allow you to set connections between leads. When the switch is in the 'left' position, the middle and the left leads are connected. When in the 'right' position, the middle and right leads are connected.

Place one of your SPDTs in column "**e**" and the other on column "**f**" such that their 3 terminals line up with the rows 25, 26 and 27.

Now test the function of the switch by connecting the left leads to Vcc and right leads to the Ground, then sliding the switch to left and right and reading the logic value on the middle lead using one of the eight logic indicators.

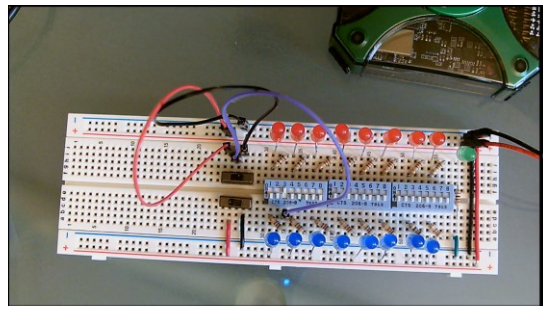

Figure 10 A snippet of the ***"Building a Fixed Test Board Tutorial"***

5.4 Preparing Video Demonstrations

In addition to written tutorials, the professor provided students with live as well as pre-recorded video tutorials. The video tutorials are a great supplement to the illustrated tutorials as they offer students two modes of instruction on performing the same tasks. Students can read the instructions, and also follow the short video clips corresponding to each section to follow the demonstration of how the task is performed by their professor. The videos are a valuable resource as students can watch them more than once when they face a problem or if they need to review a tutorial for performing a given task. A sample video demonstration of the same steps explained in the tutorial of Figure 10 is provided here.

6. Remote Course Structure and Delivery

The course professor made every effort for the online laboratory course to closely follow the format of the in-person version of the course. We followed the same check points:

1. Lecture
2. Verification of the pre-lab theoretical work
3. Verification of the simulation result (live demonstrations)
4. Verification of the behavior of the final circuit (implementation)

The course was delivered on MS Teams platform. In addition, we used our University LMS platform for sharing of the documents and course videos. The lectures were delivered synchronously, and were supplemented with detailed instructional videos that students could watch and follow at their own pace. The lectures were also recorded to help students who missed the class. When necessary live demonstrations were made using Doc Cameras sharing the instructors work with students. We used an on-line sign-up sheet to form a queue for verifying student work, and teams met 1:1 with their professor or TA online on a first-come first served basis. The professor and TA were available on MS Teams for 5 hours per lecture instead of the 3 and had extended office hours. Students were required to be logged in to MS Teams during the lab period. Professor and TA checked on students and were available for answering questions. They also verified student work at checkpoints and provided debug support.

Checkpoint1 – The pre-lab work was verified by the instructor and their TA ahead of the class, unless the work required major redo when a 1:1 video meeting was required. Students either got a green light to move to the next stage (simulation), sent brief corrections for minor errors, or asked for a short 1:1 meeting with their professor or TA to discuss the errors and how to correct them.

Checkpoint2 – Students used MS Teams to work with their partners. We accessed our simulation Tools installed on university virtual machines remotely, and students worked together by sharing their screens. When their simulations completed, or when they needed debug help, they signed up for a meeting. All the simulation results were verified live by the professor or TA remotely through sharing their screens. Depending on the size of the circuits, students were asked for applying random inputs with good coverage (determined by the instructor) or exhaustive inputs. In case of hard-to-find errors, the circuits were analyzed with the help of the professor or the TA and the necessary support was provided.

Checkpoint3 – Students worked independently on building their circuits while using MS teams and their laptop or phone cameras to share their work and progress with their lab partners and their professor or TA. This stage was different from the in-person version of the course in that each team builds one circuit in the lab, and the work is shared. This provided a learning opportunity for individual students and helped them in becoming more skillful and confident in doing experiments. When teams were satisfied with their final circuit functionality or when they hit hard debugs they signed up for 1:1 meetings with their professor or TA.

All the circuits were verified live. Students were asked to apply inputs and show the expected outputs. This practice was made possible entirely due to the use of the test-board and using methodic techniques for circuit debug. The circuit inputs were assigned following an order (numeric or alphabetic) to the input switches of the test-board, the circuit outputs or critical internal circuit nodes were assigned following an order (numeric or alphabetic) to the logic indicators (i.e. for an adder circuit, inputs A, B, C_i were mapped to switches S1, S2 and S3 and outputs C_o and SUM were mapped to Logic indicator pairs L1 and L2 respectively). It was easy to look at a pair of logic indicator diodes in a remote screen and still read the logic values '1', '0' or 'X'/'Z'. Every single circuit completed by a student was verified remotely.

The debug was undoubtfully harder in a remote setting. However, teaching good and methodic practices were very helpful to overcome this challenge. Students used identical (uniform) test-boards. During debug we helped students to move backward (from the outputs) or forward (from the inputs) in the circuit and read the physical signal values to compare with the expected values. We helped by guiding students and explaining how to proceed. Sometimes, locating the error was not possible, but incremental progress was made in a meeting to the point where the team could get unblocked and see a path to move forward with debug. In practice, the activities in this lab and our more advanced digital courses mimic the settings of the teams in industry and their brainstorming sessions. Some hard debugs needed multiple help sessions where incremental progress would eventually lead to locating the errors. On the other hand, some of the trivial and common errors such as swapping the power pins, driving an output, connecting signals to the wrong tie-point, or … were easily detectable by the professor at the first glance due to the use of a uniform test-board. There were few cases, when the remote debug was not successful and required much more independent testing on the part of the student. In a couple of cases student needed to rebuild the circuit from the scratch. In one occasion early in the semester, one of the (new) breadboards had a faulty connection and needed to be replaced. These presented hard circuit debugs that are not out of the ordinary. However, these occasional hard debugs happen in the in-person laboratory too and overall, the exercises were successful.

The online laboratory course has a big disadvantage over the in-person labs. The work demands dedication of significantly more time on the part of the instructor, the TA and the students in the course compared to the in-person version.

Even though more challenging, students successfully completed all the course projects as had been the case before the pandemic. Students' enthusiasm after completing each lab was noticeably higher upon the completion of this course compared to the in-person version. The instructor attributes this to the student expectation from an online laboratory course and how this course scored in comparison to other lab courses. Some of the student comments are provided below:

"I really liked that because this was a remote course we were able to create our own test boards. I was worried at the beginning that I would not learn a lot because of it being a remote lab, but it ended up being a very valuable learning experience."

"Was rewarding and cool to practice applying skills."

"I really appreciate this as this course was more difficult in an online environment, however, the professor made sure everyone understood and was caught up on labs. The professor and our TA , worked 1-1 to help us debug our circuits and ensure it worked properly. Looking back, I am proud of the circuits we made during our lab and it's really cool to be able to have something we hold in our hands that shows what we learned during lecture class."

"In lab, we faced many difficulties because of covid, but the professor made the experience so much better by designing specialized test boards to mimic the equipment we would have had if the lab was in person. The board was super helpful and greatly improved the lab experience. "

"The professor went above and beyond to create an at-home version of the digital lab for us to create our designs on. The labs they had created allowed for us to practice the digital design process while having fun doing it. This has been one of my favorite/most engaging labs at the university."

"The professor would go over the labs before we would complete them to make sure we would understand what we were doing; … They would have us work in partners which was really nice for debugging the circuits."

"Professor has spent countless hours working one on one with students or with small groups to ensure that everyone's work is properly analyzed. It's clear from the effort they put forward that they really care that we understand the course material."

7. Remote Course Outcomes

Every student in the course (2 sections offered) successfully completed the implementation and testing of the board. All students completed the majority of the lab experiments. The majority of students completed all the lab experiments. The percentage of students who did not complete all experiments was comparable to the standard in-person version of the course. The quality of the work was better than usual, and students mostly enjoyed the experience. There was a greater degree of excitement on the part of students around building their own board that they got to keep. Some were proud to show the board to their family and friends. This activity was a new achievement for the remote laboratory course and beyond what was done in the standard in-person version. Many students expressed much appreciation for the learning process and the methodic hands-on work they experienced in this course compared to other lab courses that were designed using ad hoc approaches. Students also gained more insight into how the lab equipment were designed and came out better prepared for the challenge of more advanced projects in their upper-level courses, their capstone projects, and in project development as a whole. This also proved a nice complement to an advanced project students did in the digital system design, a course with more theoretical emphasis, that is paired as a co-requisite with this laboratory course. In summary, our remote laboratory course performed in par if not ahead of the standard in-person version. Compared to remote courses following ad-hoc methods it made many activities possible that could not be done otherwise. Many of the advantages were discussed in section 5.1, but a quantitative comparison is not easy.

The remote debug and trouble-shooting were harder than in the standard in-person course. The average time that took for students to complete their actual work was similar to what they would have spent in the lab, but as we set up queues for getting help from the professor or TA, the wait time for receiving help was at times 50% higher than what students experienced in the lab. Some students found creative ways to deal with that by pipelining their experiments, but overall, for certain experiments requiring more support that posed a challenge as students needed to stay longer online or come to office hours to get help.

None the less, the course was very successful and achieved the main goals that were originally set for it:

(1) The successful delivery of a "*remote or personal laboratory*" that comprised of both simulation and hands-on experiments (not a *"virtual laboratory"* exclusively based on simulation)
(2) Students in the remote laboratory course completed the exact same set of experiments they would have done in the in-person laboratory course
(3) The experiments were taught methodically and by providing sufficient guidelines to students, rather than relying on them to find ad-hoc solutions and doing patchy work;
(4) Provided live (synchronous) guidance and support to students, rather than leaving them on their own;
(5) We did manage a low-cost solution and used our existing simulation software B2SPICE remotely. Our hardware budget was also reasonable (under $100 per kit), but students borrowed the already available AD2 units that they had used in the Electric Circuits course. We succeeded in keeping a reasonable budget as close as possible to the cost of the in-person laboratory.
(6) In our end of the semester assessments based on our internally designated ABET performance indicators, the course scored slightly higher (< 5%) than the in-person version of the course.

We achieved this by design of a test-board that was key element in meeting all these goals.

8. The Cost

There were two types of cost associated with the remote delivery of this course:

1. The human labor cost
2. The cost of the material

Design of the test-board that was the key element in successful remote delivery of the laboratory course, proved invaluable. We demonstrated that with the material costing less than $20 the support/test infrastructure can be built. A budget of $80 per student was sufficient to supply the entire material/tools kit for the course, aside from the AC2 units that were loaned to students that was very similar to the cost of the material and upkeep of the lab in the standard version of the course. This was also a successful experiment on how to substitute expensive lab equipment with very inexpensive test-boards that students can build themselves.

The labor cost for the professor teaching the course, as well as their TAs, was excessive. This included:

a) Design, test, and implementation of a prototype board ahead of the semester so it can be built by students during the semester
b) Planning for tools kits
c) Preparing detailed written tutorials
d) Preparing detailed videos
e) Providing support for students throughout the semester

A great deal of time was spent on items (a) and (b) during the Fall semester. Design and simplification of the board took a good number of hours and required some iterations. Also, a great deal of time was dedicated to identifying and ordering parts and tools and preparing student kits. Numerous hours were spent preparing written tutorials and video tutorials that were specifically developed for online instruction and supplemented or revised the existing tutorials that were used for instruction in the laboratory. The two sections of the lab in the standard mode demanded a total of 6 hours of in person contact per week by the professor and also by the teaching assistants. In the remote version of the course this averaged 10 hours for the teaching assistants (67% increase) and 12+ hours for the professor (over 100% increase). While teaching assistants were compensated for additional hours, the teaching load and compensation for the professor remained the same.

Overall, students in remote setting needed more contact time, as remote debug was harder and more time consuming than in person debug. Moreover, as this is generally students' first experience with doing hands on work in the field, it can initially seem daunting. They require assurance through hand-holding and one-on-one sessions. Students in remote course needed significantly more meetings to get validation of their progress. This human cost needs to be accounted for when planning for remote instruction of laboratory courses. Much of the success of this remote course was due to the instructor's willingness to volunteer their personal time for design and planning in advance of the course, and for student support throughout the semester. The same must be said of the teaching assistants who stayed long hours to support students remotely.

9. Conclusion

Students spent the first two weeks of the semester learning about and experimenting with the basic components, then used them to build and then test a solid test-board that substituted the typical training boards in digital logic laboratories. They were provided with illustrated tutorials with step-by-step directions and numerous short videos that demonstrated the assembly and wiring processes of the board. Every student built, tested, and demonstrated the correctness of their board to their professor. They then used the board as their personal laboratory infrastructure for the rest of the course.

The remote delivery of the laboratory course and the design of the test-board that made the remote delivery possible were invaluable experiences. Building the test-board proved to have many advantages over ad hoc methods of doing digital logic experiments that uses some of the same parts on the board: (1) The test-board was built once and used throughout the semester, so it saved students significant time in their experiments. In ad hoc methods, students need to add parts (e.g. switches for applying logic values to the inputs of the chips, and LEDs for reading the outputs) during each experiment. (2) After building the test-board, students could focus on the experiments and circuits without worrying about the infrastructure needed for each experiment. (3) The debug of test-board (infrastructure) was separated from the debug of the main circuit and students could deal with them separately. (4) The possibility of errors in the test logic was significantly reduced, and the debugging of the test-board was rarely required. (5) In general, the organized and methodic approach led to effective and efficient experiments, and also served as a model to think creatively and methodically for solving engineering problems. It set strong foundations for students in their future experiences.

Upon publication of this work, the author intends to make the tutorials (documents as well as the videos) publicly available, dedicated to all the youth who have the love of learning about the digital logic but don't have the means to attend universities.

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