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Dhanya Nair
Chapman University, dnair@chapman.edu

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Comments

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Online Laboratory Course using Low Tech Supplies to Introduce Digital Logic Design Concepts

Dhanya Nair
Fowler School of Engineering
Chapman University
Orange, California, USA
dnair@chapman.edu

Abstract — **This paper describes a Digital Logic Design Laboratory Course developed to engage students with hardware systems within an online setting. This is a junior level core course for students from Computer Science (CS), Computer Engineering (CE) and Electrical Engineering (EE). Hence, the laboratories are designed to provide the hands-on experience of breadboarding, testing and debugging essential to CE and EE while accommodating CS students with no prior hardware experience. Commercially available low-cost electronic trainers (portable workstations) are loaned to the students in addition to basic electronic components. To ensure a strong foundation in debugging, prior to utilizing these workstations, students are introduced to the concepts of design, build, test and debug through everyday stationary supplies and educational toys like Snap Circuits. Results from students' surveys regarding their perception of such an introduction as well as their eventual confidence in breadboarding digital logic systems is discussed. The lab structure in context of the course objectives and its implementation in an online classroom is presented. Some of the student work is included for demonstration.**

Keywords—digital logic, hands-on lab, breadboarding, remote circuit lab, project-based learning, snap circuit, digital trainers.

I. INTRODUCTION

Project-based learning (PBL) approach in Digital Logic Design (DLD) courses has shown to increase student interest [1], improve student learning experience [2-3] and the overall course satisfaction [4-5]. Hands-on laboratory components increase the students' ability to connect the theory to its practical application and hence assist in a better understanding of the material/core concepts [2,6]. Additionally, PBLs are known to provide life-long benefits to engineering students [7-8].

To incorporate this hands-on experience in DLD course, various interactive software tools have been proposed for designing and simulating digital systems [9-13] and to simulate the experience of physical breadboarding and testing [5, 11, 14-15]. Several other digital courses have been developed with projects implementing the design on FPGAs [16 – 20] and PLDs [4, 21].

Simulations by themselves may not be effective in promoting student learning but are powerful in combination with hands-on labs [22]. Building physical breadboarded circuits, either as a supplement or precursor to FPGA labs, helps students understand digital block connections better and reinforces the lecture concepts [6] while providing troubleshooting skills in the implementation and verification of digital systems [23].

The software-based labs are easiest to implement in an online/remote environment whereas the FPGA labs can also be easily implemented with just one piece of hardware. Implementing breadboard based DLD labs [1-2, 23-24] in a remote online environment poses additional challenges. The limited debugging support, limited supplies, and an inability to physically engage with other's circuit/ see their mistakes can make students shy of attempting wider digital logic applications due to a fear of destroying the physical parts.

In an online learning environment, providing students a foundation in debugging prior to introducing breadboarded circuits could help them in completing the hands-on labs successfully while having a better learning experience. This paper describes a sequence of hands-on physical labs designed using simple stationary supplies, Snap Circuits, and portable workstations to help DLD students engage in designing and debugging circuits from day one, while they were still learning the theoretical concepts.

II. COURSE BACKGROUND

At Chapman University, the DLD course is a junior-level 3-credit core course common to Computer Science (CS), Computer Engineering (CE) and Electrical Engineering (EE) students with weekly 1-credit labs (50 minutes). It is the first course introducing them to digital systems with a follow-up course on Computer Architecture based on FPGA implementation. Previously, the DLD labs were taught using only simulations and FPGA design implementations without any circuit prototyping, primarily to cater to CS students. However, with the addition of CE and EE programs, the labs were redesigned to provide students hands-on experience breadboarding and testing digital circuit components in addition to the simulations and HDL programming.

The goal was to develop a lab course that improved students experience while meeting the following student learning outcomes:

- Demonstrate the ability to breadboard, test, and debug simple digital circuits.
- Utilize electronic test bench equipment to manipulate or debug digital circuits.
- Create schematics of digital circuits on a simulation software.
- Write HDL code to describe and test digital circuits.
- Design and build simple combinational and sequential circuits, given the design criteria.

It is important to note that most of the students taking this course have no prior experience working with any electronic hardware or test equipment. Breadboarding can often be an intimidating experience for a beginner. Combining that while learning to read schematics and debug circuits can be overwhelming. This leads some students to conclude early on that engineering is hard and not for them.

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The traditional labs where exercises are derived from the lab manuals accompanying the textbook [14] provide limited opportunity to allow students to get exploratory and gain confidence in debugging circuits [1-2]. Moreover, since the labs mostly deal with the testing of individual components, the students either find it abstract and don't make the connection to the eventual application *or* get overwhelmed (especially when they struggle with reading the schematic or breadboard connections) with the knowledge that several such components would be required for even the simplest application.

This lab was taught in a fully online format (owing to COVID-19 pandemic) and each student was shipped a DLD Lab Kit including the Elenco Digital/Analog Trainer (XK-700T), Snap Kit: Digital Logic Gates (SCDLG200), electronic components box (74xx ICs, PMOS and NMOS transistors, sensors, and jumper wires).

III. Lab Structure

A. Circuit using Stationary Supplies

During the initial lab, the students are asked to design and build a circuit of their choice using stationary supplies like paperclips, paper faster, LEDs, buzzer, and sensors. The goal was to provide students the freedom to design their own individual applications, leading towards an early sense of achievement - while introducing them to basic electronic components, series-parallel connections, and open/short circuits.

A short video demonstration of the example circuit (Magic Box), based on circuit on pizza box [25] is provided to the students (Fig. 1). When the lid of the box is opened, light falls on the photoresistor (on the backside of the lid) thus reducing its resistance and completing the circuit, causing the LEDs to light up/buzzer to sound. Using everyday supplies makes the process of building and debugging circuits less intimidating while helping students learn the basic circuit concepts in a fun way.

Fig. 1. Magic Box circuit on a cardboard box lid using stationary supplies. LEDs and Buzzer can be seen on the top side while a photoresistor and the battery are on the backside of the lid.

B. Snap Circuits - Logic Gates and Circuits

All the following labs have a pre-lab assignment that is due prior to the lab time. The students receive feedback on their pre-lab design and make any corrections required during the lab time. They get started on the lab completion activity which is typically due a few days later, giving students ample time to reach out to their peers/instructor for help, if needed.

After the initial lab, students use the Snap Circuits Logic Gates and Circuits Snap Kit, to design, build and test simple digital circuits [Appendix A]. Students develop systematic debugging skills while focusing on building digital circuits with logic ICs, sensors, and pull-up/ down resistors. It thus introduces them to the physical components of digital logic, while encouraging them to experiment with the peace-of-mind that these components have an inbuilt protective circuitry.

Students are also taught how to read, draw and simulate schematics and build circuits (from schematic) while using the Snap Kit. Hence, they can focus on the schematic alone without needing to juggle breadboard connections along with it.

C. Breadboarding & Test Bench Equipment

In a traditional in-person setup, the breadboarded circuits are usually tested using an electronic testbench involving power supply, function generator, digital multimeter and possibly oscilloscope or logic analyzer. Although it is imperative for EE/CE students to learn to utilize this equipment, their full functionality is beyond the scope of CS majors.

The Digital/ Analog Trainer (Elenco XK-700) is a cost-effective (USD 200) and portable alternative to the testbench that provides a good balance in functionality. It includes power supplies (5V, 12V, 15V, analog up to 30V), function generator (ranging from 10Hz – 100kHz), potentiometers (1kΩ, 100kΩ), 8 LEDs, and 10 Switches (with 2 of them having in built debounce circuitry). Hence, it can be used as a standalone equipment for manipulating and testing digital circuits and can be combined with a multimeter/oscilloscope for analog circuits.

The labs are designed to be simple and application-oriented to engage students in an online setting (Appendix B). Since they have already been introduced to the individual components, design, and simulation earlier, the focus is on learning how to breadboard. The pre-labs require students to perform the design and simulation ahead of lab. The lab time is primarily utilized to discuss common breadboarding issues, debugging strategy and testing different sensors for real-life applications.

The students begin by building a majority voter circuit, a priority encoder circuit and then move onto more abstract 2-input CMOS logic, D Flip-Flop testing and a memory unit. Sequential design is often hard for students to grasp and building/testing circuits with feedback is a pain point. Hence, the sequential labs are designed to build upon each other with just one or two components added each time, leading towards a full finite state machine (FSM) in Lab 10 (Appendix C).

D. HDL design

The following 3-4 weeks of the lab time is set aside for students to work on their final project. Meanwhile, in the lecture component of the course, students learn Verilog programming to design combinational as well as sequential systems/FSMs. The in-lecture activities include writing design and testbench for the circuits built in lab (majority voter, priority encoder, autonomous alarm) in addition to others. These circuits are simulated, and their waveforms are compared with those from the previous SPICE simulations.

E. Final Project

Students are required to propose their own capstone projects to solve a real-world problem using an FSM with three or more states. They can work in pairs or individually and are required to present their design steps, schematic, HDL design and verification, and demonstrate the working of the final breadboarded system.

IV. Student Survey Results

Students were surveyed at the end-of-semester to evaluate their: i) interest and perceived efficacy of using Snap Circuits for understanding the digital logic concepts. ii) their overall confidence in designing, building, testing, and debugging digital logic circuits. They expressed their agreement/disagreement on a five-point Likert scale for the statements Q1-Q14 (Table 1). 19 out of 20 students completed the survey and their responses are shown in Fig. 2. Only 1 student in this class had prior experience working with hardware.

TABLE I. Survey Questions

No.	Question
Q1	I found the Magic Box Challenge (design challenge using stationary supplies) interesting and engaging.
Q2	It was easy/intuitive to understand circuit concepts (open/close, series/parallel, polarity,) using paper clips.
Q3	I felt a sense of accomplishment upon completing the Magic Box Challenge activity.
Q4	It was easy/intuitive to understand circuit concepts (open/short, pull-up/pull-down) using Snap circuits.
Q5	It was easy/intuitive to build logic using switches on Snap circuits.
Q6	I found the mischief capture challenge (Snap Circuit design challenge) interesting/engaging.
Q7	Snap circuits helped me visualize circuit building.
Q8	Snap circuits helped make the process of building circuits less intimidating for me.
Q9	Having built circuits using Snap circuits & paper clips helped me when it came to building circuits on breadboard.
Q10	It would have helped me if we omit the Snap circuit labs and started off by building circuits on breadboards.
Q11	Building circuits with real-life application (Mischief Capture, Majority Voter System, Priority Encoder, Autonomous Alarm) helped me understand digital logic better.
Q12	Using sensors helped with making the circuit applications feel more real.
Q13	I feel comfortable building and testing digital logic circuits on breadboard.
Q14	The labs prepared me for successfully completing the final project.
Q15	The sensors were adequately used in the labs.
Q16	Any additional comments?

Sensors were used in 4 (out of 6) of the breadboarded labs, as replacement to switches and to make the applications practical. Statement Q15 surveys student's perception on the inclusion of sensors in the labs. Instead of five-point Likert scale, students were given three choices to answer the statement "The sensors were adequately used in the labs.": a) They (sensors) were used more; Use them less. b) Adequately used. c) They (sensors) were used less; Use them more.

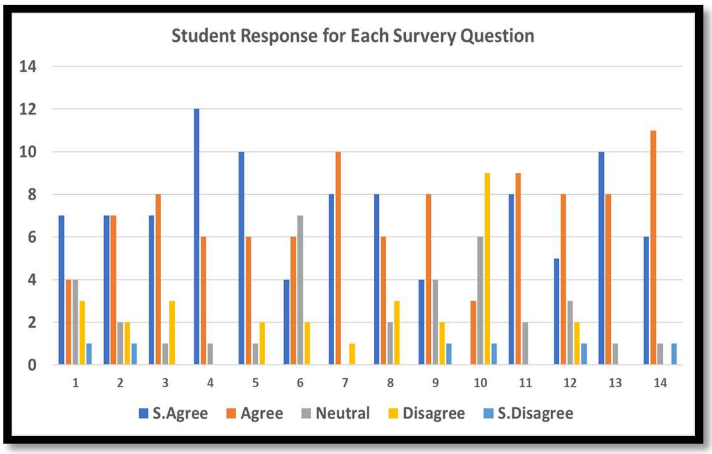


Fig. 2: Survey Results from 19 students.

A. *Circuit using Stationary Supplies*

Questions Q1- Q3 correspond to the initial lab built out of stationary supplies. Although 74% students found it easy to understand concepts using paper clips and 79% felt a sense of accomplishment upon completing this design challenge, only 58% found the activity engaging.

Following two comments specifically mentioned this lab. One student wrote that "The labs were all good labs, with the exception of the very first one that had vague requirements." and another student mentioned that "I felt embarrassed building paperclip circuits as a college student in front of my family and felt like it was a waste of time as the basic concepts we were trying to learn were thwarted by the inconsistency of paperclips".

B. *Snap Circuits*

Questions Q4-Q10 correspond to use of Snap Circuits and their perceived effectiveness. A vast majority (95%) of the students felt that Snap circuits helped visualize circuit building and simplified the circuit concepts. Despite this, some students did feel intimidated with the process of building and breadboarding.

C. *Real-life Applications*

Students responded very positively to using real-life applications in the lab assignments and felt it helped their understanding of subject matter. There was some consensus (68%) on the role of sensors to help with applications feel more real whereas 32% felt the sensors were used more and should be used less (52% felt they were used adequately, and 16% recommended using them more).

Overall, the vast majority felt they were comfortable breadboarding and testing digital circuits and felt the labs were successful in preparing them for their final project.

D. *Additional Comments*

Following is a sample of student comments regarding the labs, either provided in this survey or in the end-of-semester university course evaluation:

- Hands-on work made all the difference.
- Building circuits/breadboarding for sure is what worked well for me in this course.
- I really enjoy the labs. I seem to understand the lectures more after doing the labs.

- I have thoroughly enjoyed being hands-on with the hardware.
- I am very happy to be doing hands-on activities during labs, as I find it is easy to find myself engaged during them.
- I am very grateful to Chapman University for having the means to send lab materials to our home. It was awesome being able to build circuits despite having online learning.
- I think the videos for the prelabs and labs were the most effective in this course since it was remote.
- If there is an easier/more intuitive program than LTspice that would be nice.
- The labs were interesting, and the instructions were easy to follow... It was nice to have the lab equipment at home and still be able to do the activities hands on. I don't think this class would have been as interesting if we didn't have lab equipment.

V. Discussion

Following student work samples demonstrate some of the creative solutions generated by students to the lab design challenges.

A. Circuit using Stationary Supplies

Several of the students produced creative circuits using stationary supplies that demonstrated a clear understanding of basic circuit concepts like open/close circuit, series/parallel, and polarity (Fig. 3). During the initial weeks, students had mentioned that it was a great introduction to the concepts they were going to learn. By the semester end, however, about 21% students felt the initial challenge (designing circuits using stationary supply) was unengaging.

Although the goal of this lab was to eliminate the intimidation factor, getting the paperclips to retain tight connections can be difficult at times and may cause frustration, especially when students are working in isolation. While this might be a fun initial lab in an in-person setting to help break ice and get students excited about building, it may have limited benefits in an online setting.

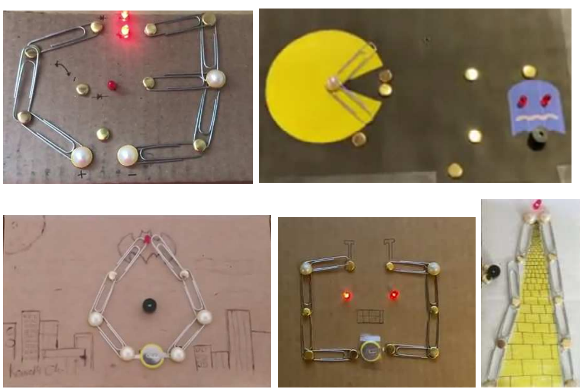
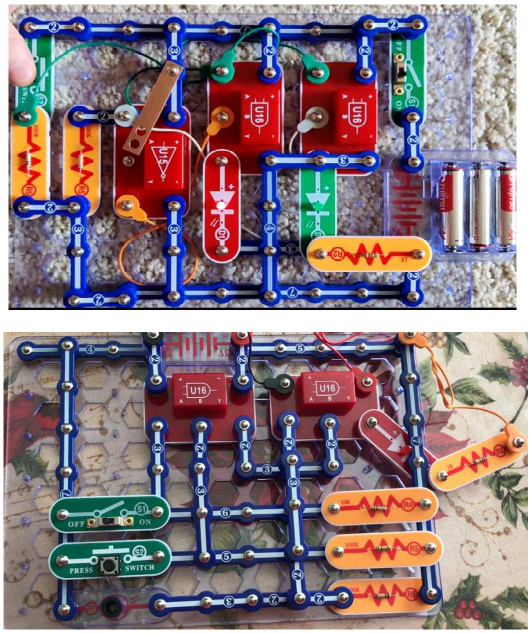


Fig. 2. Student submissions demonstrating the trolley problem, Pac-Man game, and themes like Batman, Robo, yellow brick road.

B. Snap Circuit Designs

In the first lab using snap circuits students were asked to design NAND and NOR logic using switches. While designing these circuits, students unknowingly tend to create short circuit path across the battery. Similarly, students often confuse the current limiting resistor required for LEDs with the pull-up/pull-down resistors required for inputs. Occasionally, they miss including the current limiting resistors entirely. Since all the Snap Circuit components have internal protective resistors, these incorrect connections do not cause the parts to get damaged due to excess current flow. Based on the above observations and the follow-up in-class discussions, the Snap Circuit labs appeared to help learn these key concepts in a safe and non-destructive environment, thus encouraging experimentation.

In the Snap Circuit design challenge, the only design constraint was to use at least 1 sensor for input, and to use pull-up/pull-down resistors to eliminate floating inputs. Although not required, students produced several digital logic systems involving multiple logic gates and multiple sensors. Fig. 4.a. shows a car security system that activates Red LED when the car is on (S1), and a passenger is detected (S2) but seat belt is not worn else activates the Green LED if all safety conditions are met. Similarly, Fig. 4.b. shows an airbag ready system once system is activated (S1), pressure is detected on the seat (S2) and light falls on the photoresistor (PR).



a)

b)

Fig. 4. Snap Circuit designs for car security systems showcasing digital logic circuits with multiple gates, LEDs, sensors, switches and pull down resistors.

C. Breadboarded Circuits

The digital/analog trainers were useful in providing the students an entire workbench at home for building and testing their systems. This hands-on experience working with physical components/testbench was appreciated by the students. The trainer also has internal protective circuitry that reduces the risk of hazards like shock due to leakage/excess current, hence making it a safe choice in an unsupervised online environment.

Also, no additional pull-up/pull-down resistors are required as these are already internally wired, hence simplifying the overall circuitry. The 5V power supply, clock, switches, and LEDs provided were sufficient for completing all the digital labs. The trainer costs approximately as much as a traditional engineering textbook and has the potential to be used for most undergraduate level EE/CE hardware classes. Following are student designs built/tested on the trainer.

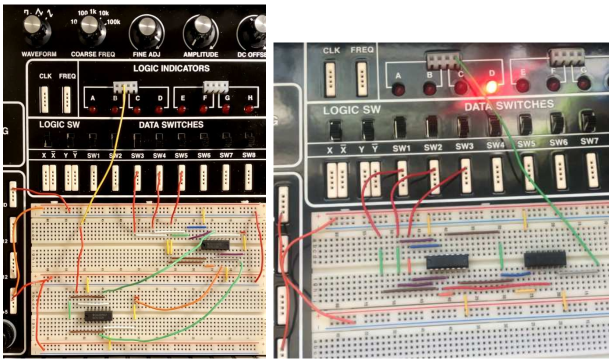


Fig. 5. Majority voter system with a) three switches off producing an off output and b) two of the three switches on produces a majority on output.

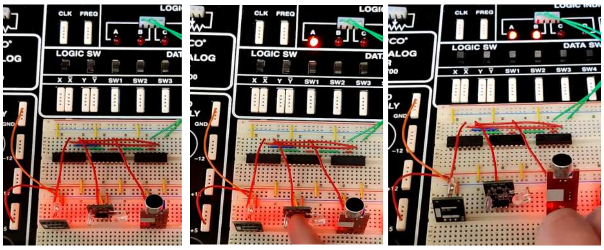


Fig. 6. Priority encoder system showing the binary number corresponding to the highest priority input sensor activated. a) when no sensor is activated, the output is 00. b) intrution sensor (center) has second priority and when activated, it shows binary 10. c) since tilt sensor (leftmost) has highest priority, once activated the output is 11 regardless of other sensor inputs.

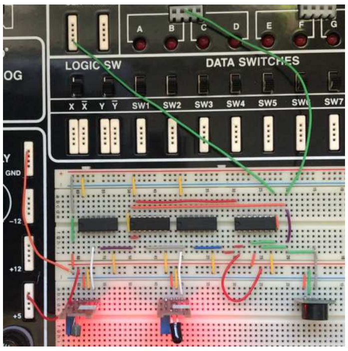


Fig. 7. Autonmous alarm system is a FSM that uses a touch sensor (leftmost), fire sensor (center), buzzer (rightmost) and the clock from the digital/analog trainer.

D. Final Project

Students proposed their own capstone projects using an FSM. Some of the projects were 3-level elevator, 2-player simultaneous ready system, random number generator on a 7-segment display, traffic light, vending machine, baseball pitch counter, passcode detector, and stopwatch. The design requirement included the use of atleast 1 sensor and atleast 3 finite states to build a real-life application. A final presentation including the design steps, simulation and verification, and final system demonstration were required.

LTSpice is a free SPICE simulator and was used for designing and simulating the schematics (Fig. 9). However, transitioning from the desired state to next is a bit challenging on LTSpice and requires complex piecewise linear modeling of the inputs. Logisim is a free digital logic simulator and is being used in the current semester. However, it does not have the ability to generate output waveforms. EDA Playground is a free tool for designing and testing HDL modules. It was used to perform Verilog design and verification of the systems.

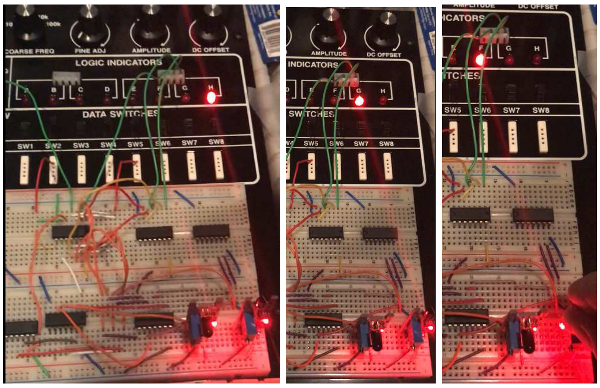


Fig. 8. Elevator system showing the elevator moving from floor 1, to floor 2 and then floor 3, based on the input from a touch sensor.

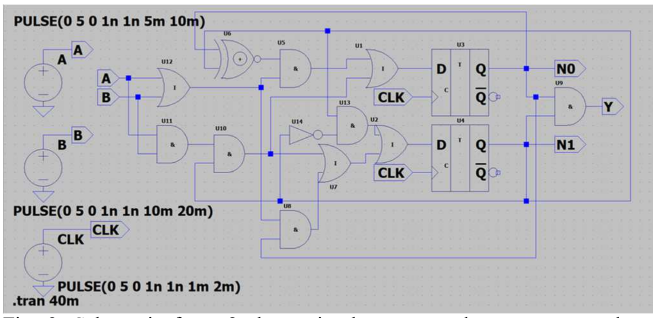


Fig. 9. Schematic for a 2-player simultaneous ready system created on LTSpice.

VI. Conclusion

Digital logic labs were designed using physical hardware components for hands-on learning in an online environment. Digital/analog trainers were distributed to students for an at-home testbench. Labs were designed to be simple yet with a practical application to captivate student interest and make it more relatable. Students were able to transfer the learnings from these labs into successful capstone projects, in an online remote learning environment. Thus, demonstrating the possibility of utilizing these labs and the portable trainers for online hands-on learning.

Prior to breadboarding, an initial lab utilized stationary supplies to build a circuit and the next few following labs used Snap Circuits Digital kit. By focusing on testing/debugging, schematics and breadboarding separately, the goal was to make circuits less intimidating and within reach of students with no prior background in electronics/engineering while giving them a strong foundation in each of the fundamental concepts.

While students developed creative projects using stationary supplies, and it might be fun lab in an in-person class, students did not find it as engaging in the online setting. The students had an overall positive impression of using real-life applications and Snap Circuits before breadboarding and were confident building and testing logic circuits on breadboard. A detailed description of all the labs along with the survey results and few excerpts from student designs were presented along with the instructor's observation during the implementation of these labs.

This course is being taught again (remotely) with 2 different instructors using the same labs, with the only difference that a different schematic simulator is being used. The semester is still in session and hence results are yet to be evaluated in comparison to this study.

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Appendices

Appendix A

Snap Circuit Labs	**Pre-Lab activity**	**In-Lab Discussion/ Activity**	**Lab completion activity**
Lab 2 (SnapCircuit Logic)	Design and build AND logic using 2-3 switches.	Test and debug the circuit. Inadvertent short circuit paths.	Design, build and test NAND and NOR logic using switches.
Lab 3 (Design Choice)	Build a logic gate testing circuit including pull-down resistors.	Pull-down vs. pull-up resistors and their effects on the circuit.	Design and demonstrate a real-life application using digital logic gate(s).
Lab 4 (Half-Adder)	Design and simulate a half-adder circuit.	Simulation waveforms. Corelating schematics to physical circuits.	Build and test the half-adder circuit.

Appendix B

Combinational Breadboarded Labs	**Pre-Lab activity**	**In-Lab Discussion/ Activity**	**Lab completion activity**
Lab 5 (Majority Voter System)	Design & simulate a 3-input majority voter.	Test an AND gate IC (74LS08). Discuss common mistakes in breadboard connections.	Demonstrate a functional majority voter system.
Lab 6 (Priority Encoder)	Design & simulate a 3-input priority encoder.	Test different sensors. Active high vs. active low operation.	Demonstrate a functional priority encoder system using inputs from 3 sensors.
Lab 7 (CMOS Logic)	Design, simulate & verify a CMOS level AND2 logic.	Build a CMOS inverter circuit on breadboard.	Demonstrate the working of AND2 logic built using CMOS transistors.

Appendix C

Sequential Breadboarded Labs	**Pre-Lab activity**	**In-Lab Discussion/ Activity**	**Lab completion activity**
Lab 8 (Testing D Flip-flop IC)	Study the IC (74LS74) datasheet and identify the different modes of operation.	Operation of preset and clear pins on the D FF IC. Generating and testing clock on the trainer.	Demonstrate the working of a D FF with input from a sensor.
Lab 9 (1-bit memory unit)	Design a 1-bit memory unit that stores a sensor value till reset.		Demonstrate the functionality of the 1-bit memory system with input from a sensor.
Lab 10 (Autonomous Alarm System)	Design & simulate an alarm system with fire sensor activating and a touch sensor deactivating an alarm.		Demonstrate the functionality of the system with sensor inputs and buzzer output.