A Novel Hybrid Approach to the Foundational Digital Systems Curriculum by Including FPGA Technology and Valuable Hands-on Experience

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Abstract

Digital Systems is one of the basic foundational courses in Electrical and Computer Engineering. The job market is increasingly in need of Electrical Engineers with knowledge of Hardware Description Languages (HDL). Yet most digital systems design curriculum, largely remains based on design using Transistor-Transistor-Logic (TTL) devices or alternatively is solely focused on FPGA design. The bipolar approaches came into focus after surveying the pedagogy and methodology that are used to teach the digital systems curriculum at different universities. The survey analysis shows how some universities have made the transition from TTL logic to an HDL approach. However, factors such as the type of university, and prerequisites need to be taken into consideration when such a conversion is going to be performed. This paper presents a novel hybrid approach to modernize the curriculum for the Digital Systems course, using traditional circuit construction, simulation software and implementation of circuits using reconfigurable logic. The goal of this curriculum is to empower the students with the necessary tools for a seamless transition from TTL devices to FPGAs, and at the same time expose them to the latest technologies in digital system design. For the instructors, this approach allows them to provide the students with more meaningful circuits that using traditional TTL devices will be too cumbersome to build on a breadboard.

Introduction

Current technology used in military, medicine, manufacturing, entertainment, and telecommunications is either partially or completely digital in nature. In consequence, Digital System Design is considered a fundamental course for Electrical Engineering and Computer Engineering programs. This course introduces students to the world of logic gates, Boolean algebra, and combinational and sequential logic circuits. Where all of these are considered the building blocks for most computer hardware (Johnson & Craig, 2002). Even more, these courses are typically offered at the freshman or sophomore level, which make them a great tool for student recruitment and retention (Shaalan, Kar, & Bachnak, 2004).

The course is traditionally taught using TTL gates where the students wire Integrated-Circuits (ICs) chips on a breadboard, providing them with great hands-on experience. However, when the complexity of the circuit increase it becomes difficult to build and debug on a breadboard. This is due to the number of ICs and connections that are required. As a result, most of the complex circuits are analyzed using only simulation software, hindering the feeling of excitement obtained from building something physical.

In the last few years, there has been a trend due to rapid advances in technology to teach these courses using Hardware Description Languages (HDL) (Loo, Planting, & Murdock, 2006) (Hasan, 2009) (Tabrizi, 2017). This same trend can also be observed in the job market where more engineers are required to be proficient in HDL since it is the market standard for Digital Systems Design. Without a doubt, the availability of Complex Programmable Logic Devices (CPLD) and Field Programmable Gate Arrays (FPGA) has changed the world of digital systems design. Now it is possible to design digital systems and deploy them to reconfigurable logic devices without placing a single IC on a breadboard.

The idea of teaching digital systems using HDL provides many benefits. One of them is that students will be familiar with software and hardware that it is used in industry. However, one major drawback is that students will lose the haptic feedback from building circuits (Zhao & Huang, 2017). Another issue may be the requirement that students have to learn VHDL or Verilog programming before taking the course. Nevertheless, the progress of technology is immutable, and educators will have to adapt to these challenges with innovative approaches (Shayesteh, Rizkalla, Christopher, & Miled, 2016) (Yilmazer, Yilmaz, & Seker, 2011).

This paper has two goals. The first goal is to inform the faculty about the current state of digital systems curriculum at several academic institutions. This is achieved by providing sample data that has been collected from 27 universities that had courses in Digital Systems within the Electrical Engineering program. The data was primarily collected from university websites. The schools were chosen randomly and the breakdown with respect to their classification is as follows: 9 non-Ph.D. granting, 18 Ph.D. granting; 4 private, 23 public; 13 highly selective, 14 not highly selective; Geographical location – 5 West, 6 East, 4 Southeast, 2 Midwest, 1 Northwest, 9 Southwest; Carnegie classification – 18 doctoral, 7 masters, 1 bachelors and 1 community college. The second goal is to provide the faculty with a novel curriculum that can be used to modernize the course. For that reason, a hybrid digital system curriculum is presented, in which traditional TTL devices are used for basic logic circuits. Advanced digital circuits such as sequential systems are implemented using the Basys 3 FPGA board and Multisim. At the end, the students will be able to recognize the current state of technology, and how advanced digital systems are implemented in the real world. Even more, students will be exposed to HDL programing, sparking their interest for more advanced courses within the curriculum.

Curriculum and Pedagogy

This section presents an analysis of the curriculum and pedagogy used at different universities where digital systems courses are being required. Furthermore, this section summarizes the various methodologies and materials used to teach this course.

Curriculum Analysis

Prerequisites are a major issue when any part of a program is updated or modified. This determines if the students possess the necessary skills to understand the materials and perform as desired. The basic questions that need to be answered are: What do we want the students to know by the time they take the course? Do the students need to have knowledge of a programming language? Do they need to know about FPGAs and their architecture? By surveying the curriculum at other universities around the United States, we can provide a picture of what other institutions are doing, and how they are answering these questions. Figure 1a shows a frequency distribution of the instructional year within the Electrical Engineering degree plan for Digital Systems courses at different universities. Notice that most of the degree plans place their digital systems course during the sophomore year. In Figure 1b, we present which prerequisites are required for the course. This information was collected from the course syllabi published online. From the data, it can be observed that several universities require some type of programming in order to take the course. However, it was found that at least six of the surveyed universities do not have any prerequisites at all.

The next question that needs to be answered is: How many universities have revamped their digital system curriculum to use the HDL based approach? The answer to this question can be found in Figure 2a. This presents an analysis of the frequency distribution of pedagogy for digital systems courses. Finally, every syllabus was analyzed looking for any patterns regarding prerequisites, and curriculum placement. The data was broken down into universities that use a chip-based approach or the HDL approach. In addition, the number of universities that have a programming prerequisite was also considered. Furthermore, the number of universities that place the course during the freshman year or the sophomore year were tallied and plotted for each case. The results from this analysis are summarized in Figure 2b.

The data reveals that of the 14 universities using the HDL approach, 10 have a programming prerequisite. Four of the universities place this course in the freshmen year, while the remaining 10 place it at the sophomore year. On the other hand, of the 13 universities using the traditional approach, 6 of them require programming to take the course. Furthermore, 6 of the universities place the course in the freshman year, while the remaining 7 place it in the sophomore year. It appears that the HDL based courses are more likely to have programming as a prerequisite and be offered in the sophomore year. Keep in mind that this survey was done considering Ph.D. and non-Ph.D. granting institutions. It appears that many Ph.D. granting institutions will introduce the course early on their curriculum. More information for this analysis can be found in the document "A Survey of Digital Systems Curriculum and Pedagogy in Electrical and Computer Engineering Programs (Ochoa & Shirvaikar, 2018). This effort was the stepping stone for the proposed curriculum presented later in this paper.

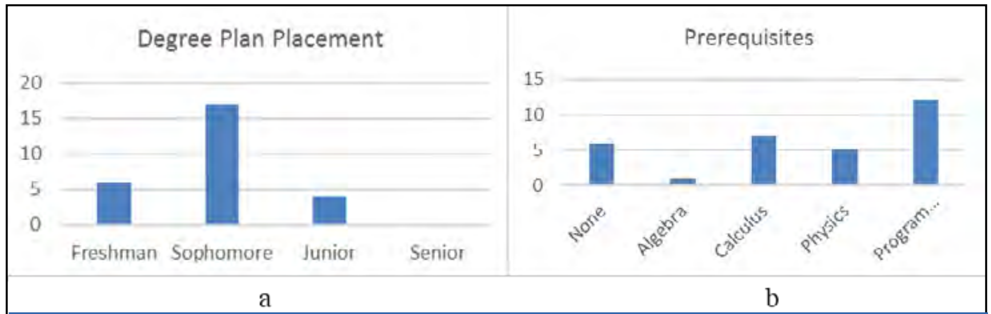

Figure 1. a) Frequency distribution of instructional year within the Electrical Engineering degree plan for Digital Systems courses at different universities, b) Frequency distribution of prerequisites for Digital Systems courses at different universities.

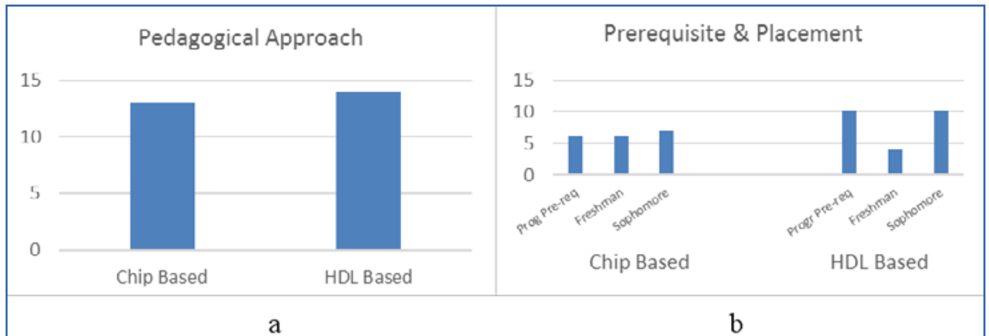

Figure 2. a) Frequency distribution of Pedagogy for Digital Systems courses at different universities (HDL – Hardware Description Language) b) Programing prerequisites, and program placement based on the course pedagogy.

Basys 3 FPGA Board, and Multisim

FPGA technology came from Programable Read-Only Memory (PROM) and programmable logic devices (PLDs) which could be programmed from the factory or in the field. FPGAs are designed to be configured by the customer or designer after they have been manufactured. Hardware Description Languages (HDL) are used to configure or design circuits in the FPGA board. They contain an array of programmable logic blocks, and a hierarchy of reconfigurable interconnects that allow the blocks to be "wired together." Logic blocks can be configured to perform complex combinational functions, or merely simple logic gates like AND- and XOR-gates. In most FPGAs, logic blocks also include memory elements, which may be simple flip-flops or more complex blocks of memory. Many of them can be reprogrammed to implement different logic functions, allowing for flexible reconfigurable computing.

The Basys 3 is an entry-level FPGA development board designed exclusively for the Vivado Design Suite, featuring Xilinx Artix-7 FPGA architecture. This board is the newest addition to the popular Basys line of FPGA development boards, and is perfectly suited for students or beginners just getting started with FPGA technology. This board was chosen for this course because it is relatively cheap and has all the necessary features for an entry level learner. The most important feature for this project was its easy integration with National Instruments (NI) Multisim.

Multisim Design Suite Student Edition is required for the successful implementation of the proposed curriculum. The success of this approach is hinged on the fact that Multisim can convert a graphical design made through component pick and place through a graphical interface into HDL code that can be loaded into an FPGA board. Multisim 14.1 and newer versions are capable of converting a design into HDL code. National Instruments and Digilent provide tutorials on how to program FPGA boards using Multisim (National Instruments, 2017) (Digilent, 2019).

Proposed Curriculum

The curriculum that will be presented in this section was designed based on the course EENG 3302 - Digital Systems offered at The University of Texas at Tyler. This is a 3-credit hour course with two hours of lecture, and a three-hour laboratory per week. The ABET Course Learning Outcomes (CLO) for the laboratory section are listed below.

1. Use modern engineering tools including modeling and simulation software and virtual instruments
2. Perform laboratory experiments utilizing digital system analysis, design and implementation techniques
3. Prepare laboratory reports that clearly communicate experimental information in a logical and scientific manner

and the topics covered on a regular semester are presented in Table 1.

The proposed changes to the curriculum mainly affect the laboratory component of the course. Currently, the laboratory implementation is a two-fold, either through wiring of TTL basic gates on a solderless breadboard or by simulation on NI Multisim. The simple circuits are implemented by wiring the components in the form of TTL chips on a solderless breadboard, and their functionality is tested by connecting LEDs and switch buttons. As the complexity of the circuits increases, it becomes more difficult to wire them on a breadboard, and even some of the sequential circuits are prone to error if a large amount of wiring is involved. In such instances, the circuits are simulated on Multisim Design Suite from National Instruments (NI). The suite is equipped with a virtual instrumentation to allow the students to test and simulate their circuits within the program.

As it was mentioned, most of the advanced circuits cannot be built and tested in a traditional laboratory setup, and most of the analysis is done in simulation. This removes the excitement and satisfaction of building something that works. The proposed curriculum makes use of the Basys 3 FPGA board to bring more complex circuits to the physical world where the students will be able to test their behavior. The idea is not to use FPGAs for every single experiment, but to use it with circuits that are too complex to be implemented in the laboratory. These changes only affect the mode of implementation of the laboratory exercises that are tough to implement on a breadboard and easy to implement on the Basys 3 board. The peripherals included on the Basys 3 board are more than enough for the entry level FPGA programming. Table 2 shows the proposed laboratory curriculum. Two combinational circuit laboratory exercises and one sequential laboratory have been modified so that they can be implemented on the Basys 3 FPGA board. Also, at the end of the semester, the students have the opportunity to implement a circuit that will emulate the behavior of an elevator. The authors of this paper will be more than happy to share the laboratory procedures with any instructor interested in implementing these changes.

Course Topics	
Introductory digital concepts	Number systems, operations and codes
Logic gates	Boolean Algebra and logic simplification
Karnaugh Maps	Combinational Logic
Flip-Flops and related devices	Counters, Shift registers, and sequential logic
Memory and storage	Introduction to microprocessors
Integrated Circuit technologies	

Table 1. Topics covered in a regular semester

No	Lab Title	Experiment Goals	Implementation
0	Instruments	To familiarize the students to the lab instruments and how to use them	
1	Logic gates and Boolean Algebra.	Test and observe the working of basic gates AND, OR, NAND, XOR, NOR, NOT.	On the breadboard using TTL chips and LED's.
2	De Morgan's Theorems	To verify De Morgan's Theorems of Boolean Algebra.	On the breadboard using TTL chips and LED's.
3	Combination Circuits	To simplify Boolean expressions to the simplest form and construct the simplest form and compare with the original form.	Simulate on Multisim using the Word generator and Logical analyzer
4	Universal property of NAND and NOR.	Verify the use of the universal gates as AND, NOT and OR gates.	On the breadboard using TTL chips and LED's.
5	Adders and Multiplexers	To implement an ADDER and a Data Selector and analyze its output.	Simulate on Multisim using the Word generator and Logical analyzer
6	Encoders and Decoders	To implement an Encoder and a Decoder circuit.	Simulate on Multisim using the Word generator and Logical analyzer
7	**Seven Segment Display**	**To implement a BCD decoder with the seven-segment display.**	**On the Multisim software and Bassys-3 FPGA board.**
8	**Comparators**	**Implement a comparator circuit**	**On the Multisim software and Basys 3 FPGA board**
9	Look Ahead Carry Adders	Implement the Look ahead carry adder.	Simulate on Multisim using the Word generator and Logical analyzer
10	Arithmetic and Logic Unit	Implement a simple ALU.	Simulate on Multisim using the Word generator and Logical analyzer
11	Latches and Flipflops	Implement the flipflops	Simulate on Multisim using the Word generator and Logical analyzer
12	**Counters**	**Implement a BCD decade counter**	**On the Multisim software and Basys 3 FPGA board.**

Table 2. Proposed laboratory curriculum for the modernized digital systems course. This curriculum assumes a semester in which 13 laboratory sessions could be allocated.

Assessment Method	Laboratories to be Assessed	CLO
Laboratory Report	Labs: 1, 5, 7, 11, 12	3
Practical Exam	Middle: Labs 1-6 End: Labs 6-12	2
Final Project Presentation	Elevator Problem	1

Table 3. Assessment of laboratory procedures, and student success.

The students' performance is measured using three different assessment methods. The first assessment method requires the students to write laboratory reports based on the results obtained from the experiment. The second assessment method is composed of two practical exams. One exam will be at the middle of the semester, and it will measure the students' ability to build simple TTL circuits from a given schematic. The other exam will be at the end of the semester, and it will measure the students' ability to solve sequential systems, and their implementation using FPGAs. For the last assessment, the students will need to design an elevator circuit using sequential systems and implement it using FPGAs. The student will be assessed based on the circuit functionality. Table 3 summarizes the assessment methods used to evaluate the learning effectiveness of the proposed curriculum, and their mapping to the Course Learning Objectives.

Example Laboratory Procedure

In this section, we present a snapshot of how "Laboratory 7 – Seven Segment Display" is implemented using the Basys 3 FPGA Board.

1. Using Karnaugh maps, the students will design the

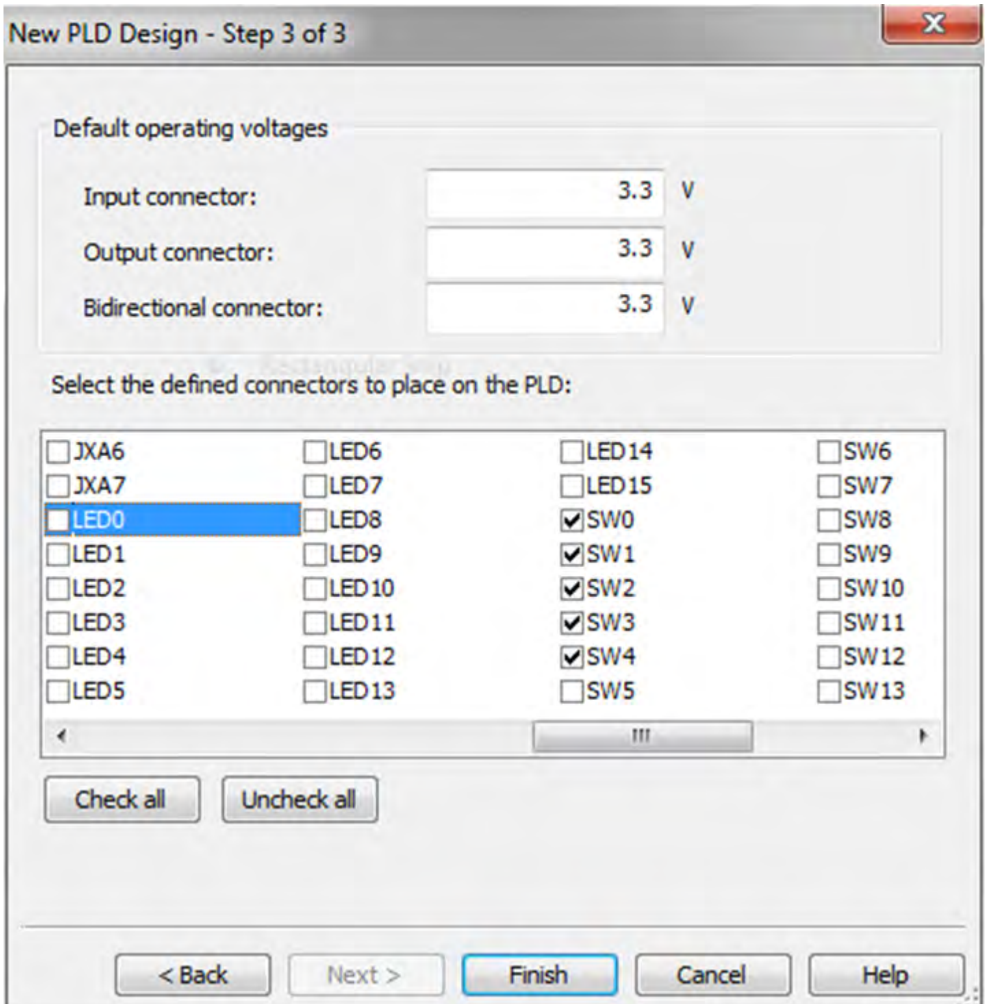

Figure 3. Selection of inputs and outputs for the Basys 3 board in Multisim.

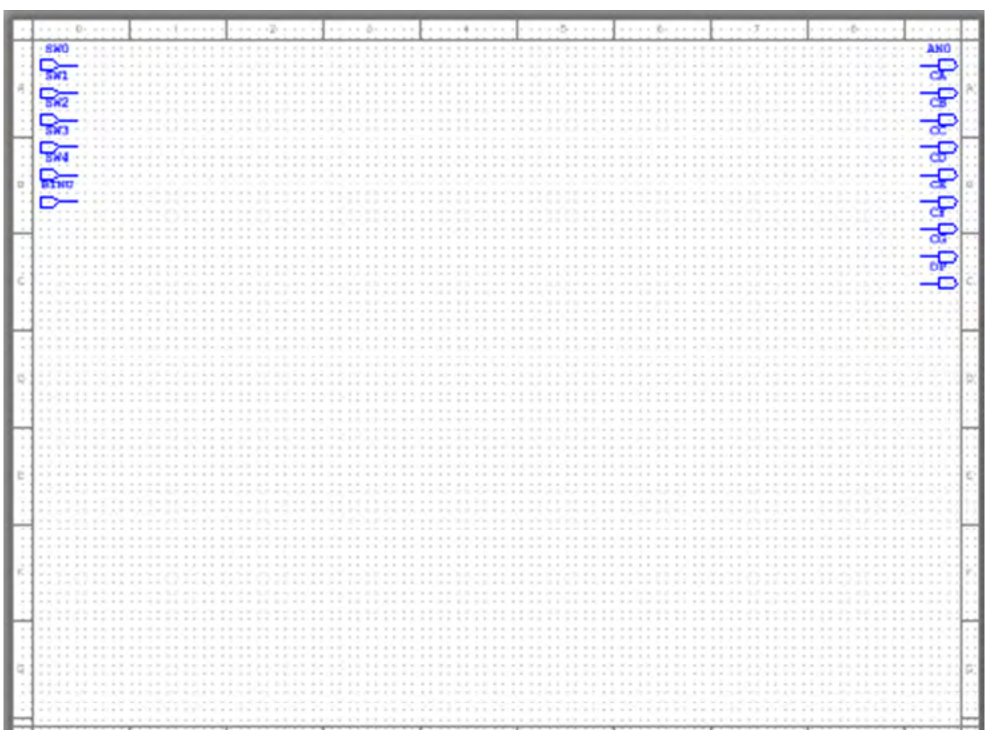

Figure 4. Blank Multisim project with the selected I/O ports available.

logic circuit necessary to control the seven segments of the display.

2. Once the student has a logic expression, it will be used to create the circuit in Multisim to download it later to the Basys 3 Board. During the setup of the project, the students will need to select the desired inputs and output from the FPGA to make the connections. Figure 3 shows how the inputs and outputs of the board are selected.
3. Once the students selected all the necessary inputs and outputs, a blank project will automatically open in Multisim with the selected I/O ports available in the project. Figure 4 shows how the empty project looks in Multisim, with the inputs on the left and the outputs on the right.
4. At this point, the students are ready to start building the digital circuit in Multisim, and connect the proper inputs, and outputs to the logic circuit.
5. Once the circuit is complete, it can be transferred to the Basys 3 board. With the FPGA properly programmed, the students are ready to start testing their design.

Conclusion

Digital Systems is considered one of the core courses in electrical engineering and computer engineering curriculums. However, most of the courses offered at the universities still rely on traditional approaches to provide hands-on experience to the students. In this paper, information regarding the pedagogy, curriculum placement, and pre-requisites used at universities across the country was presented. From the collected data, it was observed that some of the universities had already updated their digital systems curriculums to include current technology, but still there are many universities that need to take a step forward and make the changes. This is important not only to have a more up-to-date curriculum, but also to prepare the students for their future careers.

In addition to the data presented in this paper, a hybrid digital systems curriculum was presented. This provides the students with the opportunity to experience traditional laboratory hands-on experience using TTL devices, but also interact and program with current FPGA technology using Multisim and the Basys 3 FPGA board. This curriculum is designed to make the transition from TTL devices to FPGA very simple for the instructors and the students. Allowing the instructors to prepare more meaningful experiments, in which the student will design circuits and deploy them into reconfigurable hardware will be a major advantage. Our hybrid approach will familiarize the students with modern tools and design paradigms. Moreover, the observation of snippets of basic HDL code will lay the foundation for the study of this topic, which the students may learn later in advanced digital systems courses. This exposure will give them a better understanding on how digital systems are deployed in industry. The authors of these papers are willing to share the curriculum and laboratory procedures with digital systems instructors interested in revamping their courses.

References

Digilent. (2019, July 25). *Programming Digilent FPGA Boards Through Multisim*. Retrieved from Digilent: https://reference.digilentinc.com/learn/programmable-logic/tutorials/program_fpgas_through_multisim/start

Hasan, M. (2009). Course Development In Digital Systems Targeting Reconfigurable Hardware. *2009 Annual Conference & Exposition* (pp. 14.373.1 - 14.373.9). Austin, Texas: ASEE.

Johnson, M. J., & Craig, B. (2002). Computer Systems Pedagogy Using Digital Logic Simulation. *International Conference on Computers in Education, 2002. Proceedings* (pp. 703-704). Auckland, New Zealand: IEEE.

Loo, S. M., Planting, A., & Murdock, M. (2006). Introducing Field Programmable Gate Arrays Into Sophomore Digital Circuits Course. *2006 Annual Conference & Exposition* (pp. 11.832.1 - 11.832.7). Chicago, Illinois: ASEE.

National Instruments. (2017, November 22). *Getting Started with Digilent Boards in Multisim*. Retrieved from National Instrumments: http://www.ni.com/tutorial/14871/en/

Ochoa, H. A., & Shirvaikar, M. V. (2018). A Survey of Digital Systems Curriculum and Pedagogy in Electrical and Computer Engineering Programs. *2018 ASEE Gulf-Southwest Section Annual Meeting*. Austin, Texas: ASEE.

Onyango, B. H., Ochoa, H. A., & Shirvaikar, M. V. (2019). Modernization of Curriculum for the Undergraduate Digital Systems Course. *Proceedings of the 2019 ASEE Gulf-Southwest Annual Conference*. Tyler, Texas: ASEE.

Shaalan, H., Kar, D., & Bachnak, R. (2004). Digital Systems Laboratory For Teaching And Research. *2004 Annual Conference* (pp. 9.464.1 - 9.464.10). Salt Lake City, Utah: ASEE.

Shayesteh, S., Rizkalla, M., Christopher, L., & Miled, Z. B. (2016). Attached Learning Model for First Digital System Design Course in ECE Program. *2016 ASEE Annual Conference & Exposition*. New Orleans, Louisiana: ASEE.

Tabrizi, N. (2017). First Course in VHDL Modeling and FPGA Synthesis of Digital Systems. *2017 ASEE Annual Conference & Exposition*. Columbus, Ohio: ASEE.

Yilmazer, N., Yilmaz, M., & Seker, R. (2011). A Project-Based Hands-On Digital Logic Course. *2011 ASEE Annual Conference & Exposition* (pp. 22.89.1 - 22.89.10). Vancouver, BC: ASEE.

Zhao, Y., & Huang, S. (2017). Improving Student Understanding of Digital Systems Design with VHDL via Inductive Instruction. *2017 ASEE Annual Conference & Exposition*. Columbus, Ohio: ASEE.

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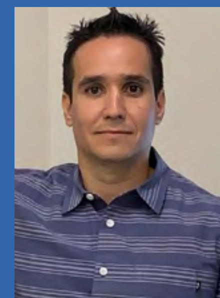

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