Evolving Circuit Design Education: Comparing Traditional Wiring with Digital Approaches

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Abstract

Traditional electrical engineering laboratories have long emphasized hand-wiring individual components, fostering foundational skills in circuit design and troubleshooting. However, feedback from industry advisors has underscored the growing importance of introducing students to FPGA (Field Programmable Gate Array) technology, which better reflects current trends in embedded systems development and hardware-software co-design. This paper explores the pedagogical and practical implications of transitioning from traditional hand-wired laboratory exercises to an FPGA-based instructional approach. While the adoption of FPGA technology offers students exposure to modern design methodologies and real-world applications, it also raises concerns about the potential decline in hands-on wiring experience. This skill is critical for developing troubleshooting capabilities, which are essential for advanced coursework and professional practice in electrical engineering. To evaluate the impact of this shift, the study implemented identical laboratory topics using both physical wiring and FPGA-based designs. Student performance was measured using key metrics, including troubleshooting efficiency, task completion time, and design accuracy, providing a comprehensive analysis of learning outcomes. This study aims to identify effective strategies for integrating emerging technologies into engineering curricula without compromising the development of fundamental hands-on skills. The findings offer valuable insights into optimizing engineering education, ensuring students are well-equipped to meet industry demands while retaining the practical competencies essential for success in the field of electrical engineering.

Keywords: *FPGA, Circuits, Teaching, Laboratory*

1. Introduction

The foundational equipment and circuits used in introductory electrical engineering laboratories have remained largely unchanged for decades. However, modern engineering increasingly emphasizes integrated devices such as Field Programmable Gate Arrays (FPGAs) over individual components. This evolution presents a trade-off between teaching hands-on debugging skills or teaching hardware programming skills.
At Embry-Riddle Aeronautical University, the CEC-222 Digital Circuit Design course, taken by computer science, electrical, and computer engineering majors, recently shifted from a physical wiring-focused curriculum to one centered on FPGA-based digital design. This transition provides an opportunity to compare the impact of these approaches on students' skill development and foundational understanding. The FPGA-based labs emphasize troubleshooting and programming in digital environments, contrasting with the hands-on challenges of traditional physical wiring. While FPGA skills are highly relevant for computer science students focused on digital systems, practical wiring skills remain essential for electrical engineers working with circuit design and troubleshooting.
This paper evaluates the educational outcomes of this shift by analyzing student performance in both lab formats. Metrics including task completion time, accuracy, and troubleshooting efficiency were used to assess skill development and preparedness.

2. Literature Review

A literature review about the integration of FPGAs into courses has been broken down into several categories

- Implementation of FPGAs within different courses
- Project and remote learning with FPGAs

There have been several advancements within digital circuit design. Leading many to upgrade from simple wiring labs to gauge students' understanding of the course material. This research aims to look at the effect of using FPGAs. Researchers like Professor Gehrig looked at a basic implementation of this approach: "we can only recommend using FPGAs in education. Their flexibility and quick programmability allow interesting and diverse problem statements. By using real hardware instead of a simulator, the students also must cope with the 'real' problems of digital design such as good placement, economical routing, timing, and synchronization between components" [2].
Several others have implemented FPGAs within digital systems designs classes and laboratories and have used them to help students understand the different concepts the class covers [3, 6, 7, 9, 10, 12, 16]. Or others have already made entire courses focused on this subject [4, 17, 19]. Several others have begun using FPGAs for classes like signal processing or computer architecture [8, 11, 14, 15, 18].
Another approach taken has been using them to make a project-based class. Professor Araujo takes this approach and notes, "The course structure, oriented to the development of real working digital systems, challenges the students and increases their motivation. This way, the learning process is improved, and the classes are more productive" [5].
The pandemic accelerated the need for remote learning solutions, leading to innovative applications of FPGAs in virtual environments. For instance, Professor Morgan describes the development of the Web-based Remote FPGA Lab, which "helps students to understand and reason about digital system operation, using interactive animation of signal behavior in an executing digital logic system at any level of the design hierarchy" [20]. Many others believe this will be helpful as it will help students work at their own pace more efficiently as stated by Professor Rajasekhar where they state, "Remote labs provide greater accessibility which has the potential of opening more opportunities to learn. For one, it increases the ability of a student to explore on their own. Second, it allows the student to do their assignment on their own schedule. Traditionally, a student needs to be physically present at the lab" [21]. Many more have begun implementing remote FGPA labs for different classes like low-power design, digital systems design [22-30].
While this study was not preplanned or designed to be a controlled experiment, it leveraged the opportunity presented by the ongoing changes in the course curriculum to analyze the impact of transitioning from traditional wiring labs to FPGA-based labs.

3. Experimentation

To evaluate the impact of transitioning from traditional wiring to FPGA-based digital design in the CEC-222 Digital Circuit Design laboratory course, the researchers conducted two separate experimental setups across the semester. The experiment involved 80 students from four sections of the CEC-222 course, with each section comprising approximately 20 students. Each section participated in two experimental setups throughout the semester that utilized different implementation formats for the same topic. The first experiment, conducted earlier in the semester, focused on introductory skills, while the second centered on more complex concepts using latch design. These experiments were comprised of two different lab sessions. In one session, students performed physical wiring on breadboards using integrated circuits, while in the other, they used FPGA technology with Verilog programming. By examining student performance across these two related experimental phases, the researchers sought to identify how students' skills and understanding evolved in response to different lab formats.

3.1 Lab Set I

In the first experiment, foundational concepts in digital circuit design were introduced through basic logic gate implementations. Each student group participated in two lab sessions covering the same topic of basic logic gates but utilized distinct implementation methods.
The first lab session focused on building simple circuits using integrated circuits (ICs) where the students would go through the process of wiring a four input and gate, then move onto a four input or gate. The students were then instructed to attempt to build a four-input gate for NAND and NOR gates, with the catch that they had to identify the second type of gate to make it a true four input NAND or NOR gate. An example of a 4 input AND gate circuit schematic that the students had to put together can be seen in Figure 1.

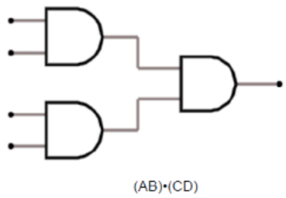

Fig. 1 Schematic of a 4 input AND gate created in lab 1.

In the second lab, students used FPGA technology, programming the same basic gate circuits in Verilog on an FPGA board. An example of Verilog code implementing a 3 input AND gate that the students had to put together can be seen in Figure 2. Both lab sessions required students to design, implement, and troubleshoot circuits of low complexity.

```
module Lab3_and(
    input [15:0] sw,
    output [15:0] led);

    assign led[2]=sw[2]; //Show the switch positions
    assign led[1]=sw[1]; //Show the switch positions
    assign led[0]=sw[0]; //Show the switch positions

    and a1 (led[15],sw[2],sw[1],sw[0]);
endmodule
```

Fig. 2 Coding implementation of a 3 input AND gate created in lab 2.

Below is the averages between the two laboratories as shown in Table 1.

	Section 1	Section 2	Section 3	Section 4
Wiring Lab	90.11%	91.25%	85.79%	82.6%
Verilog Lab	98.72%	97.35%	89.11%	91.6%

Table 1. Average Student Scores on the First Lab Set.

3.2 Lab Set 2

The second experiment, conducted later in the semester, extended these foundational skills by focusing on latch design using similar physical and digital implementation methods, but with a greater focus on circuit complexity. They completed two lab sessions that covered the same topic, latches.
In both sessions, students were tasked with creating an RS-latch using NOR logic gates, an RS-latch using NAND logic gates, and a final latch using a combination of NAND and NOR gates, ensuring comparable instruction on latch design and troubleshooting in each format. An example of the physical circuit schematic of an RS-latch using NOR gates that the students had to make can be seen below in Figure 3.

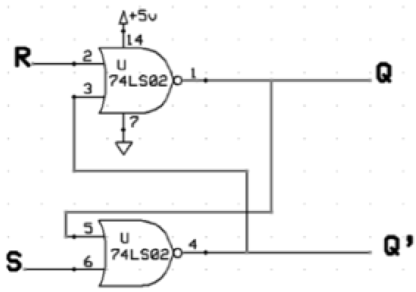

Fig 3. Physical Circuit Schematic of RS-Latch using NOR Logic Gates.

An example of the Verilog implementation of an RS-latch using NOR gates in Vivado that the students had to make can be seen below in Figure 4.

```
module RS_Latch_nor(
input R,S,
output Q,Q_);

    begin
    nor A(Q, R, Q_);
    nor B(Q_, S, Q);
    end

endmodule

module RS_Latch_test(
input clk,
input [15:0] sw,
output [15:0] led);

assign led[1:0]=sw[1:0];
//instantiate your latch here
RS_Latch_nor R1(.Q(led[15]),.Q_(led[14]),.S(sw[0]),.R(sw[1]));

endmodule
```

Fig 4. Coding Implementation of RS-Latch Using NOR Gates.

The second experiment also assessed task completion time, accuracy, and level of student struggle. In examining the average time taken by students to complete the final two experimental labs, a slight but notable difference emerged. Students generally completed the wiring lab faster, with Sections 3 and 4 averaging 45 minutes, compared to an average of 1 hour for the Verilog lab. The averages for the labs can be seen below in Table 2.

	Section 1	Section 2	Section 3	Section 4
Wiring Lab	96.28%	96.3%	77.95%	75.6%
Verilog Lab	86.5%	92.35%	70.58%	81.15%

Table 2. Average Student Scores on the Second Lab Set.

4. Discussion

For consistency, all students completed the wiring lab first, followed by the FPGA-based Verilog lab. The performance metrics assessed in this initial experiment included the time taken to complete each lab, the accuracy of their answers, and how much students overall seemed to struggle with each lab.
In analyzing the time taken by students to complete each lab in the first experiment, it was observed that, on average, students finished the wiring lab faster than the Verilog-based FPGA lab. Specifically, sections 3 and 4 completed the wiring lab with an average time of 1.5 hours, while the Verilog lab required an average of 2 hours to complete. This difference in completion time likely reflects students' relative familiarity with each lab format at this point in the course, as the wiring lab marked their second encounter with physical circuit design, while the Verilog lab was their first experience with digital design and coding in Verilog.
In Section 1, students achieved higher accuracy in the wiring-based RS-latch lab, with an average score of 96.28%, compared to 86.5% for the Verilog lab, leading to a 9.7% difference between the average scores. For Section 2, however, the gap between the wiring and Verilog labs was less pronounced. Here, the Verilog lab accuracy reached 92.35%, just slightly lower than the 96.3% for the wiring lab, and leading to a 3.95% difference.
In comparing student struggles between the final two experimental labs, distinct challenges were observed with each format. For the wiring lab, many students continued to grapple with translating the given circuit diagram into a physical layout on the breadboard, particularly when handling connections for inputs, power, ground, and interpreting LED outputs. The need to manage physical components, such as wiring understanding power and ground, presented obstacles for students, some of whom found it difficult to visualize the abstract circuit as a tangible system, especially with the more complex circuits necessary to create the RS-latch. Additionally, the troubleshooting process in the wiring lab proved complex, students frequently needed instructor assistance to diagnose and resolve physical connection errors.
In contrast, the Verilog lab appeared to present fewer conceptual translation issues. Students seemed more adept at representing logic gate functions in Verilog code, and inputs through switches and interpreting output directly through the board's LEDs also felt more intuitive for the students, who generally had less difficulty understanding this setup. As shown in Table 2, the results between Sections 1 and 2 indicate different trends compared to the first set of labs.
Small errors in syntax, such as Verilog syntax missing semicolons, incorrect module declarations, or misaligned logic definitions frequently tripped up students, and the unfamiliarity with Vivado's project setup added another layer of difficulty.

Students also completed a post-lab survey after completing the two latch labs. Data from both experiments were collected and logged for each metric by the lab administrators at the end of each lab session based on observations throughout the lab and a lab document the students had to complete following each lab, allowing a somewhat detailed analysis of student performance across the semester. The survey responses from students enrolled in the course revealed different preferences and perspectives on FPGA-based versus traditional wiring labs. With 33 students expressing a preference for FPGA labs and 25 favoring traditional wiring, a significant portion of students find the FPGA-based approach advantageous. However, an additional 22 students indicated an appreciation for both methods, recognizing the educational value in each.

A common theme among those who preferred FPGA labs is the perceived alignment of FPGA skills with industry practices, especially for students majoring in computer science or software engineering. As one student noted, “I prefer the FPGA implementation because it’s more applicable to industries today and makes more sense conceptually.” Another student highlighted that the coding aspect of FPGA labs allowed for easier debugging: “The FPGA implementation is easier to use and takes less time to fix errors and run the program.”

On the other hand, students who favor wiring labs emphasized the hands-on nature of this method, which they believe enhances their understanding of physical circuit construction and troubleshooting. One student articulated, “I prefer the wiring labs compared to the FPGA labs because I understand things better when they are in a tactile format. Physically wiring a circuit allows me to better understand how it works compared to writing Verilog code for a circuit.” Another student appreciated that wiring labs offered fewer opportunities to rely on external assistance, such as AI tools, saying, “For wiring, you cannot use ChatGPT or other AI tools, you need to think by yourself.” These comments show the value some students find in wiring labs for developing practical skills that may be important for future courses in electrical engineering.

For students who expressed a preference for both lab formats, their responses showed that each approach offers unique insights that contribute to understanding digital circuit design. One student reflected, “I think that doing labs with just one or the other would leave a gap of important knowledge. They’re both valuable to teach.”

Challenges were noted for both lab formats. Students working with FPGAs frequently reported issues with Verilog syntax and software-related delays, with one student mentioning, “With Verilog coding, there are very minor mistakes that can completely ruin your entire program.” Meanwhile, wiring labs posed their own obstacles, such as faulty components or time-consuming troubleshooting, which one student described as “annoying mistakes that can nullify a significant amount of effort due to a single misplaced wire.”

5. Conclusion

The findings of this study show how engineering education is evolving, potentially going from traditional approaches to digital methodologies. This research aimed to investigate the benefits of replacing wiring laboratories with FPGA-based assessments, considering students’ feedback and performance. The study revealed that each method offers distinct advantages, where wiring labs enhance foundational understanding through tactile experiences, while FPGA labs align with industry-relevant digital design practices. The students were assessed on both methodologies, recording a higher overall average on FPGA labs. However, the survey results revealed divergent student preferences, suggesting that neither approach should stand alone. Instead, a balanced integration of both formats could provide a comprehensive educational experience, allowing students to be equipped with both practical hardware skills and digital proficiency. Furthermore, the challenges identified in both lab formats, such as Verilog syntax errors in FPGA labs and time-consuming troubleshooting in wiring labs, highlighted the need for improved instructional strategies. Thus, teachers could help students entering the real engineering world more effectively by adopting a hybrid approach that combines the strengths of each method. Technology continues to evolve, and curricula has to adapt to maintain essential hands-on skills and take advantage of digital advancements.

The study highlighted the trade-offs between traditional wiring and FPGA-based labs by analyzing student performance across different metrics. For instance, in the RS-latch lab, students in Section 1 achieved higher accuracy in the wiring-based approach (96.28%) compared to the FPGA-based approach (86.5%), indicating the effectiveness of hands-on methods for certain tasks. However, in simpler labs such as the Verilog implementation of basic logic gates, FPGA-based labs showed an average improvement of 9% in accuracy for Section 1 (98.72% in FPGA vs. 90.11% in wiring). The advantages and disadvantages of each method are summarized below:

Lab Type	Advantages	Disadvantages
Traditional Wiring Lab	1. Hands-on experience with physical circuit building. 2. Improves understanding of physical wiring and troubleshooting. 3. Develops tactile and practical skills essential for future courses in electrical engineering.	1. Time-consuming troubleshooting due to physical errors (e.g., loose wires). 2. Limited scalability for complex designs. 3. Requires physical components that can malfunction or break.
FPGA-Based Lab	1. Aligns closely with modern industry practices. 2. Easier debugging	1. Steeper learning curve for syntax and software tools (e.g., Verilog).

Table 3. Advantages and Disadvantages of Wiring and FPGA Labs

These findings suggest that while FPGA labs are good in developing precision and proficiency for coding tasks, wiring labs are important for giving the students a deeper understanding of physical circuit design and troubleshooting. This shows the importance of integrating both methodologies to balance industry-relevant skills with foundational engineering principles. Therefore, this research encourages integrating digital implementations with traditional wiring methods to allow students to have a complete and broad background.

6. Future Research

Future research will focus on developing a hybrid implementation of the class that integrates both traditional wiring and FPGA approaches to optimize students' learning in digital circuit design. This could help students develop more skills and explore a curriculum aligned to industries. One key aspect could be evaluating students' performance across different metrics, such as problem-solving efficiency, troubleshooting, and conceptual understanding, to identify the strengths and limitations of each method. Additionally, longitudinal studies could determine how the combination of physical and digital methods prepare for advanced courses and professional challenges. This research will aim to bridge the gap between traditional and modern educational approaches, trying to create a more comprehensive framework for engineering students.

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