Digital Design and Programmable Logic Boards: Do Students Actually Learn More?

Thomas Weng, Yi Zhu and Chung-Kuan Cheng

Department of Computer Science and Engineering
University of California, San Diego
9500 Gilman Dr., La Jolla, CA 92093-0404, U.S.A.
tweng.y2zhu,kuan}@cs.ucsd.edu

Abstract—Digital design classes are increasingly using programmable logic devices (PLD) to augment the educational experience. Previous works discuss the advantages of using PLDs, such as Complex Programmable Logic Devices (CPLDs) and Field Programmable Gate Arrays (FPGA), in digital logic design education and highlight the instructor’s experience of integrating these teaching methods in the classroom. This paper instead focuses on the students’ experience to determine the overall effectiveness of using PLD boards. By using statistics from a comprehensive survey that targets student feedback and opinion, and by comparing our class’s final exam scores with a previous class that did not use PLDs, we are able to informatively assess the benefits of using PLDs for digital design education.

Index Terms—Digital logic design, CPLD board, Undergraduate, Laboratory

I. INTRODUCTION

Although digital design is an essential part of the computer science curriculum, challenges remain in teaching this subject effectively to computer science students. These challenges include a lack of previous hardware class work and possible disinterest in hardware among computer science students [1].

For the academic term of Spring 2007, the Altera UP-2 board was used in the digital logic class CSE140L taught at University of California at San Diego (UCSD) for computer science majors. Previous classes used only logic simulation for the digital logic design lab work. The switch requires a significant time commitment, but previous research reveals that students enjoy using programmable logic to augment their education [2], and we feel that the use of programmable logic is beneficial.

In this paper, we present our research results on the overall impact of using PLD boards. We describe our experiences in using them, what works, and what can be improved. We analyze the students’ reaction and perception of using the boards, and finally try to answer the question of whether the students learned more by using reprogrammable logic.

Section II examines previous work and related efforts towards teaching digital design. Section III describes the class, its goals and objectives, and the lab assignments. Section IV discusses the teaching methodology and experiences. Section V presents the results of a survey handed out to the students at the end of the term. Section VI compares the results between the students’ exam scores of this term against a previous class that did not use a PLD board. Section VII compares our own experiences with those of previous studies and research. Finally, we present the conclusion in Section VIII.

II. PREVIOUS WORK

Advancing VLSI technology has made development boards with reprogrammable logic cheap enough to be used for educational purposes [2]. Electrical engineering and computer engineering curricula have long since used CPLD boards and other forms of reprogrammable logic to augment the educational experience. For example, Newman [3] uses the Altera UP-1 board to design robots in their digital logic design class, and Maurer [4] argues that electronic design automation (EDA) is in fact essential to computer engineering education.

In computer science, however, debates continue on the benefits of using PLD boards in a computer science classroom [1]. Concerns include whether or not computer science students have the proper background [1], and the amount of difficulty in teaching students VHDL and integrating it into the introductory digital logic design courses.

Strong arguments have been made, however, that computer science students can still benefit from using these boards, as building real hardware allows students to gain a better understanding of the material [5]. Also, students can grasp the full design implementation cycle, which is invaluable in terms of real world experience [6]. Nickels [7] weighs the pros and cons of using programmable logic and concludes that while there are some drawbacks, there is much to be gained from using it, especially with regards to introducing more complex designs.

Indeed, programmable logic is used in computer architecture classes [8]. Such efforts recognize the value of allowing students to implement and test their processor designs in actual hardware, as opposed to just running simulations [9]. The experiences from these efforts show that including EDA tools and programmable logic for computer architecture courses is extremely beneficial to students taking such classes [10].

Past works also discuss methodologies to best use programmable logic in design courses. Kleinfelder et al. [11] discusses one approach to teaching digital design using CAD...
tools and hardware description languages, and suggests a hierarchical approach where students first learn simple logic circuits and move up to more complex problems. Nixon [12] presents teaching digital design using a purely programmable approach, and states that it is possible to introduce all major concepts in digital design.

Teaching digital logic using rapid prototyping of hardware designs is also reviewed. Williams et al. [13] present an outline for teaching computer design using virtual prototyping, and discuss the methodology and tools that were used. Zemva et al. [14] also presents an environment for prototyping hardware on FPGAs to teach digital design. Compelling arguments are made that students can benefit from completing the entire design cycle from design to actual hardware implementation.

One goal that almost all of the previous work emphasize is that of ensuring a high quality of lecture and lab materials. Amaral et al. [1], for example, state that as the software environment had fewer glitches, the quality of the teaching improved, and the feedback from the students taking the class became more positive. Calazans and Moraes [2] suggest that ensuring sufficient resources with regard to the PLD boards is important.

III. CLASS STRUCTURE AND LAB ASSIGNMENTS

CSE140 is the introductory digital logic design course at UCSD for students in the computer science program [15]. This class covers the theoretical aspects of digital design, including combinational and sequential logic, standard modules such as decoders and multiplexers, and system design.

The majority of the students taking this class have very limited exposure to electrical engineering, and for many this will be their first class involving hardware. Therefore, some basic fundamentals of digital logic are also reviewed, such as boolean algebra and circuit theory.

The associated lab class CSE140L covers the practical aspects of digital design in a laboratory setting [16]. This class has four labs, with each lab covering a topic related to the material taught in CSE140. The material taught in the class includes basic transistors and hardware description languages such as VHDL.

The students used the Quartus II software to make their designs using both schematic capture and VHDL. The designs are then tested using functional and timing simulations, and finally downloaded into the UP-2 CPLD board. The students are required to form pairs of two and each pair is required to needed purchase a CPLD board which costs 100 US dollars.

The four labs are as follows:

1) **Combinational Circuit Design:** This lab introduces combinational logic and contains five circuits to be designed, including a 1-bit adder and a 2-to-1 multiplexer. The purpose of the first lab is to allow the students to become familiar with the Quartus II tool and the PLD board. Students learn how to design the basic combinational circuits, how to build modules and how to take advantage of hierarchy, and how to verify and validate a design using both simulations and the PLD board.

2) **The specification and usage of flip-flops:** This lab focuses on synchronous logic and also contains five circuits. Students are required to implement shift registers, synchronous and asynchronous counters, a pseudo-random sequencer, and a clock circuit. Students learn how flip-flops work and how to design synchronous circuits.

3) **Finite state machines:** This lab asks students to design finite state machines (FSM) for three circuits: a traffic light circuit which simulates the sort of a traffic light one would find at a street intersection, a train circuit that simulates the control system for a train, and a gray counter. Students are required to use both schematic diagrams and VHDL codes to implement the FSMs, and to understand the difference between Mealy and Moore FSMs.

4) **CPU design:** The last lab lets students build a mini central processing unit (CPU) consisting of a program counter, an arithmetic logic unit (ALU), an instruction decoder, three register files, and instruction memory. The design is implemented on the PLD board, and allows students to test and use their CPU on the actual board. The assignment teaches students system design and brings together all that they learned during the academic term.

IV. TEACHING METHODOLOGY AND EXPERIENCES

Students usually take this class at the end of their second year or the beginning of their third year, and are required to have taken basic programming and assembly [15]. The amount of electrical engineering experience among the students taking this class is limited, with the majority of students never having taken any electrical engineering classes. In addition, many students have not taken the computational theory class either, and therefore do not have previous exposure to finite state machines.

As the majority of the class having limited knowledge of concepts related to digital logic design, we sought to truly integrate the PLD board with the labs to give the students a concrete experience in digital logic design. To that end, we had two broad goals we wanted to achieve. First, we wanted to promote learning for the students. Second, we wanted to design labs that would be enjoyable and educational for the students. The PLD board, as shown in Fig. 1, has only two push buttons and 8 switches as inputs, and 2 LED digits as outputs. Thus, it would be a challenge to design labs that could utilize the limited resources to demonstrate different logic designs, from a simple adder or multiplexer, to a CPU with complex structures.

The first goal was met by designing the labs to reflect the material that was currently being taught, while the second was met by designing labs that were novel and had a degree of fun to them. To this end, every lab had at least one entertaining additional project, in addition to the core academic projects. Throughout the entire class, the boards were used to show students the practical aspects of digital design, in order for them to better understand the theoretical aspects. The use of
I enjoyed using the CPLD board 1 1 3 8 22 4.40
I enjoyed running functional and timing simulations 15 10 7 0 3 2.03
I learned a lot from using the CPLD board 0 0 7 9 19 4.34
I learned a lot from running functional and timing simulations 5 5 17 5 3 2.89
The tutorials are helpful 0 0 0 10 25 4.71
The tutorials are misleading 19 13 2 1 0 1.57
Debugging using board display is effective in helping me figure out what is wrong 2 4 10 9 10 3.90
Debugging using functional/timing diagram is effective helping me figure out what is wrong 12 7 10 4 1 2.31
Using the CPLD board allowed me to learn digital logic design a lot more than if we did not use it 0 0 8 6 21 4.37
The tutorials are helpful 0 0 0 10 25 4.71
The web board is helpful 1 0 5 12 17 4.26
The experience of using Quartus II and CPLD board will strengthen my resume 2 3 5 8 17 4.00

1: Strongly Disagree; 2: Disagree; 3: Neutral; 4: Agree; 5: Strongly Agree

TABLE I
SURVEY QUESTION RESULTS

Fig. 1. The PLD Board

Dual digit 7 segment display
FPGA
Push button 8 input switches

Fig. 2. The Display of Train

a board allows students to literally see their circuit. The two most popular labs (as voted by the students) are presented as an example of the approach used in designing these labs.

1) Train: This problem is borrowed from Hamblen and Furman [17]. Students were to design an FSM for a train controller, which controls two trains on three tracks to avoid collisions. The results are shown on a computer monitor, as shown in Fig. 2. The key to this lab was allowing students to “free-play” and design different controls for the simulated train, and then to see the results instantly on the screen. This problem was the only one that makes use of the VGA monitor to show the design results. We provided all the logistic codes for display to the students, as we wanted them to focus on the understanding of finite state machine concept and design approaches. In addition to the standard correct solution, we also inspired the students to design different finite state machines that could make the trains to “crash” and gave them bonus points. The students showed great interests in “play” with this problem: each group proposed different rules to make the trains “crashed”, and we believed they gained better understandings after “playing”. This lab was voted the most liked by the students. This lab problem was the first assignment that required the students to learn VHDL. We gave them the majority of the framework, but had them modify a few VHDL statements to learn how VHDL models the underlying hardware. This was a gentle introduction to HDLs, as we did not want the students to be intimidated by having to learn them.

2) CPU design: This lab assignment required the students to design a working mini-CPU, with data and control subsystems. This was the final one of the labs in the class, and brought together all of the previous content, such as combinational circuits and sequential circuits. Various results will be produced in each cycle, when the assembly code is running in the CPU. In the previous classes, students had to observe the results via simulation graphs, which would be a nightmare for them to debug. This project was the most time-consuming, but the students remarked that they learned a great deal on computer architecture and the role of designing modules. The students were taught on how to break down the
problem into modules, and combining the modules using buses at the system level.

With a board to use, however, the students were able to see their CPU design results shown in the LED digits, where the instruction ID and result are shown in the two LED digits respectively. That makes the testing and debugging become much easier, and also enables us to design more complex instruction sets, e.g., including branch instruction in the instruction set and asking students to run programs containing loops in their designs, which was extremely tedious to verify using simulation diagrams but very easy to observe using the PLD board.

In all of the lab assignments, detailed instructions and tutorials were given to students as guidelines. The prototyping design flow is important, but it should not be over-emphasized as this was not a major objective of this class. Therefore, detailed tutorials were crafted for the labs that emphasized the digital logic instead of the actual software. This step was important, as having students struggle with the EDA tool would only discourage students from the entire process.

We maintained a web forum that the students were encouraged to post questions on, and actively answered their queries in a timely manner. We felt this was also very useful to have, as this allowed constant communication between the students and the instructors over the academic term. Because the whole class had access, any issues one student had could be efficiently relayed to the rest of the students.

From observations in lab, office hours, and general feedback over the course of the quarter, we felt that the PLD board helped the students, not only in their learning, but also in their enjoyment of the class. Many students mentioned that using the board really reinforced what they were learning in class. Interestingly, we observed that many students did not like running logic simulations.

The most interesting observation that we made was that the students who struggled with learning these concepts seemed to benefit most from using the boards. Interacting with them, it was apparent that by concretely seeing digital logic being prototyped on their boards, that they were gaining a better understanding of the core material. Many of these students would tell teaching assistants during office and lab hours, that seeing the results on the boards motivated them to continue to work on the problems.

V. SURVEY AND STUDENT FEEDBACK

We asked the students to fill out a comprehensive survey on their opinions and experiences with the digital design labs. We collected 35 returned surveys out of the 38 students in class, i.e. 92.1% of students responded.

The first part of the survey instructed the students to read a series of statements, and give each statement a score from 1 to 5, with 1 indicating that they strongly disagreed with the statement, a 3 indicating they were neutral about the statement, and a 5 indicating that they strongly agreed with the statement. Table I details the results of this first part, where columns 2–6 list the number of students who gave different scores for each survey question respectively, and the last column gives the average scores.

The second part of the survey asked the students a series of short-answer questions. Questions asked included what their experience of the academic term was like compared with their initial expectation, how the PLD boards helped their understanding of digital design, and what they would change about the course.

According to the first part of the survey, the great majority (86%) enjoyed using the PLD board (Question 1), while only 3 students (9%) enjoyed running simulations (Question 2). Likewise, 80% of the students felt that they learned digital logic from using the PLD board (Question 3), while only 23% felt that they learned from using the simulations (Question 4). Not a single student disagreed with the statement that using the PLD board helped them learn digital design, and a significant 77% did agree (Question 9).

In the second part, we asked the students whether they would have understood digital logic design as well if they did not have boards to use (i.e. they only had functional and timing simulations). 63% of the students stated that they would not have learned the contents as well without the board; 26% said they would have spent a lot of time and effort to grasp the knowledge without the board; only 4 students (11%) thought the boards were not useful.

When asked to compare the PLD board and the simulations, most students said that they liked to see the output results on the board. Many students remarked that it was much easier for them to identify the errors and check the functionalities on the board, rather than checking timing and functional diagrams. One student stated that the board allowed him to see errors in his logic diagrams, while another student stated “I thought it was really neat to be able to see the number 32 instead of 10000 with high and lows in a timing diagram.”

Our survey also revealed that the majority of the students enjoyed the lab problems that allowed them to use the PLD board to its maximum potential. One student commented, “it (the PLD board) allowed me to apply concepts learned in class in a real world situation and understand how people in the industry go about using these concepts to solve these problems”. This point is reflected in the students’ opinions on the labs. Table II shows the three best and the three worst problems as voted by the students. The problems that received the most votes tended to be the problems that fully utilized the board, and modeled real world problems, as opposed to an academic exercise such as constructing an adder.

Indeed, the most popular lab was the “train” lab, where students used VHDL to design a control system for a train that could be displayed on a computer monitor. One student stated that he was able to “see what happens when you do various things, getting the hang of VHDL.”

Conversely, the students disliked the problems which were time consuming and academic in nature. The “Gray Counter” and “Johnson Counter” problems were unpopular, despite
TABLE II

<table>
<thead>
<tr>
<th>Best Problems</th>
<th>Votes</th>
<th>Worst Problems</th>
<th>Votes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train</td>
<td>26 (74%)</td>
<td>Gray Counter</td>
<td>15 (43%)</td>
</tr>
<tr>
<td>CPU Design</td>
<td>19 (54%)</td>
<td>Traffic Light</td>
<td>11 (31%)</td>
</tr>
<tr>
<td>Clock</td>
<td>11 (31%)</td>
<td>Johnson Counter</td>
<td>7 (20%)</td>
</tr>
</tbody>
</table>

Fig. 3. Final Exam Score Distribution in Fall 05 and Spring 07

being basic sequential circuits. The students still commented that seeing the actual digits helped them understand both circuits however. This we felt was tremendously important, as in the end, we wanted the students to learn the fundamentals of digital design.

The tutorials we prepared were universally well received. Every student felt that the tutorials were helpful, with 71% strongly agreeing with that statement (Question 5). This result indicates that providing detailed tutorials was an important part of teaching the lab portion of the class, as we did not want the students to struggle with the tool at the expense of learning the material. This approach seemed to work well as 91% of the students felt that the tutorials are clear and not misleading (Question 6). Despite that, there were portions in the tutorials that could have been better. We focused on the PLD board to the detriment of clearly explaining the importance of simulations, which might partly explain why the general reaction to simulations were negative.

One significant drawback of using a PLD board is the cost. The survey results show that many students felt the board was too expensive. Only 28% of the students felt that the PLD board was worth $100, while a full 40% felt that the board was not worth $100 (Question 13). Offering lab boards for students to use (in a school computer lab, for example) would be one possible solution to this issue. This approach would mean that students would no longer be required to purchase a board for personal use.

VI. FINAL EXAM COMPARISON RESULTS

The students stated that they felt the boards made a positive impact in their learning, but we wanted to see whether the students did in fact learn more by using these boards. It is of course difficult to determine quantitatively the amount that a student has learned, so we use as proxy the final exam scores of the main digital logic design class.

The previous time this class was taught by the same instructor was during the Fall term of 2005. The CSE140 final exam scores for the two terms are compared in Fig. 3. At the upper end, the two classes performed equivalently. For both terms, half the class scored between 90 and 100. The percentage of students that scored between 80 and 90 however jumped significantly in the second term (with the boards), from 20% of the class up to 30% of the class. Additionally, in the recent term nobody scored between 30 to 49, as did a few students from the previous term.

The data supports what we already observed — the top students did not seem to benefit greatly, but rather it was the second tier students that seemed to benefit the most. From the survey comments, many students remarked that the use of the board solidified many of the concepts they were learning in the class. We feel that the PLD board did indeed help students learn, and that the benefit was most prominent among students who might have otherwise struggled with the material.

The survey results from those students who scored between 80 to 90 support this claim. All such students agreed that they learned more from the PLD board; 100% of them thought the tutorials are useful and appropriate; and all but one student stated that the course was more interesting than they originally expected. One student said “This class is very useful and I have learned a lot from it, especially lab 4 because I really got to see how things are done.” Another student said “At first I thought it would just be another class to drag myself to everyday. However, I now have a great appreciation for digital design. So much so that I am considering a career on it.”

We believed that the results demonstrate that using a PLD board has significant benefits in teaching a digital logic design class. Students who otherwise might be turned off by a hardware class were instead able to see real applications beyond just theory. This helped these students grasp the important concepts behind digital logic design, and played a vital role in keeping their interest in the subject material over the academic term.

VII. COMPARISON WITH PREVIOUS WORK

We compare our results and experiences with the previous studies. Our paper differed from previous work in that we wanted to determine if using programmable logic and hardware helps students learn, but we are still able to compare and contrast our experiences with that of past research.

Amaral et al. presented their students with a survey and their results showed that the students largely enjoyed the lab exercises, despite the additional challenges required [1]. This matches with our own experiences, as our students also felt that having the PLD board was worthwhile despite the additional effort required to use one.

This positive experience is repeated in several other studies. Calazans’ survey results show for example that the students largely enjoyed being able to use programmable logic [2]. All the previous work we examined that included a discussion on student feedback agreed with this, and our own experiences largely agreed.

Previous work however differed from our own methodology in some areas. Vera et al mentioned that their students enjoyed
being able to develop projects dynamically [6]. Our labs were more static, and the feedback we received indicated that our students would have enjoyed more free play. This is one area we will attempt to change in the future.

Additionally, we note that other works have varied in their emphasis on the roll of simulations, HDLs, and actual hardware. Areobi mentioned some of the difficulties in teaching VHDL in a first course on digital logic design [5], so we sought to ease our students into learning and using an HDL. Several papers stated that having high quality laboratory experiments was important, with no glitches and bugs to negatively affect the learning process. Thus was a key goal we spent much effort to achieve, double checking our own labs and tutorials on the boards to make sure everything was correct. Our results show that the effort was worthwhile, as the students appreciated the tutorials and overall had positive comments on the course and lab quality.

VIII. Conclusion

In this paper, we investigated whether using a programmable logic device board helps computer science students learn digital logic design. We introduced PLD boards as a critical component of our lab assignments, and monitored the student’s reactions. The students then answered a detailed survey on what they thought of the course, including whether they thought the boards were useful and helped them learn the material.

From our observations and the survey results, we found that the students as a whole did enjoy using the board, and felt that it helped them learn the material. The ability to concretely see their implementations was of significant benefit to many of the students in the class. We found that the students who normally might have struggled in the class seemed to benefit the most from the board.

We also described what we thought worked and what we thought could be improved. We felt that the quality of the lab materials was important, and that the students enjoyed the labs. However, some felt that more open-ended ones would have been useful. We also would have emphasized more the importance of simulations in the design process.

We compared the class final exam scores against a previous term’s, and note that while at the top the scores were the same, there was a significant improvement in the middle score range. While it is impossible to truly gauge the amount the students actually learned, the results along with their comments suggest that the PLD board did make a difference. From the survey results and our own observations, the experience for the students was positive, and we feel that using a PLD board did indeed improve the quality of education for the class.

ACKNOWLEDGMENT

The authors thank the support by National Science Foundation through award NSF CCF-0618163.

REFERENCES