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DIGITAL ELECTRONICS: A MODERN LAB APPROACH

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Abstract: *The paper presents a set of lab applications for students in Electronics, Computers and Telecommunication. The proposed lab applications are a blended learning approach mixing a "classic hardware oriented lab" and a "modern/abstract/virtual lab" using programmable logic devices. The set of labs are based on XILINX FPGA development boards and free software development tools. The paper presents statistical data of the student evaluation for these labs.*

Key words: *digital electronics lab, Xilinx FPGA, blended learning.*

1. Introduction

Digital Electronics course became a "classic subject". However, updating the lab applications to meet the current development in this field and motivating students to focus on digital hardware world is not an easy task.

The author's experience on teaching *Digital Electronics* course and labs is that many students can easily understand Boolean algebra's but they face problems using it for a real design.

There is always a debate regarding *Digital Electronics Laboratory* content:

• **"Hardware approach"**: real digital integrated circuits, professional equipment for signal generation and visualization (Figure 1).

• **"Software approach"**: virtual instruments (developed in LabView), remote access lab, development workbench with re-programmable devices, circuit simulation software or hardware description language (HDL) simulators.

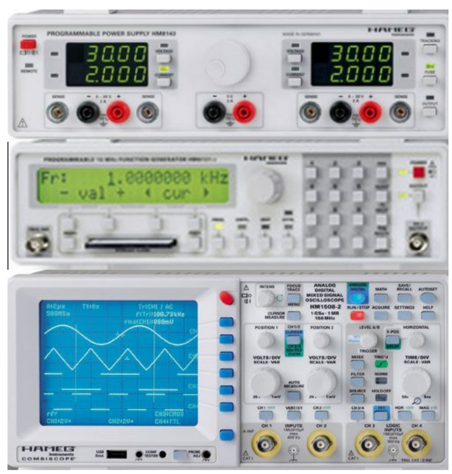

Fig. 1. *Stackable set of electronic equipment used for lab applications: power supply, signal generator and analog/digital oscilloscope*

Both approaches have pro and cons.

Using real stuff (equipment, signals and circuits) is good for presenting students the real life of test and debug in electronics (hardware engineer). Virtualization is good

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for easy and fast understanding of concepts (hardware designer).

The approach of studying basic digital circuits on simulator [8-9] seems to be very convenient for developing design experience. However, when the product comes to the prototype debug stage, the "simulation experience" is not enough for bringing up real digital integrated circuits. The author proposal is not to use simulation during the introductory course but for practicing HDLs.

Which approach is better for students? Which one is enjoyed by students? Which approach is better for future engineers?

Motivating the students for studying digital electronics is not easy. An abstract view (including a PC) seems to be more attractive and, in the same time, cheaper for the university. However, this is not enough for the industry that asks graduates for more real, practical and operational knowledge. The lab should close the gap between students/university satisfaction and students/engineers and industry satisfaction.

2. State of the Art in Digital Electronics Lab

Some universities, Iaşi [7], Baia Mare [4] and Cluj [8], use to follow the *Digital Electronics* course chapters and to propose to build digital circuits from logic gates, flip-flops and to do simple applications with registers, counters, finite state machines and on-the shelf digital integrated circuits.

Other universities, Bucharest [9], presents advanced topics in digital world (like noise in digital circuits) and advanced HDLs design subjects.

There are also universities, University of Illinois at Urbana-Champaign [10], that use Electronic Workbench software for teaching basic discrete logic circuits.

The author experience at Braşov is similar to the one presented at Cluj [6]. Relevant benefits (for acceptable costs) were observed if the university provide students with unlimited access to the programmable boards in digital design education, allowing hands-on experiences outside traditional laboratory settings.

3. Objectives

The proposed lab applications combine these two approaches for offering student a blended learning approach [1] that gives them, in the same time, real knowledge and immediate satisfaction:

- using real equipment for real signal generation and visualization and
- using a development platform for fast prototyping of small logic circuit, including a PC.

The lab topics are similar to any *Digital Electronics* course [5]. The novelty of the proposal consists in the variety of practical activities offered during the semester following the course, for securing the students knowledge:

- access to real/professional equipments;
- students having their own programmable hardware systems and unrestricted access to the most commonly used design tools;
- students having at their own places software simulation of hardware.

Having programmable hardware at their disposal, students are able to experiment advanced subjects like platforms to create a new class of digital circuits that can address the issues of large circuit design [2-3].

4. Laboratory Logistics and Operation

4.1. The Digital Electronics Course

The lab follows a course of *Digital Electronics*. The course presents classic chapters but also HDL models for each basic circuit. The HDL approach fulfills the student expectation of "abstract model" and shows them the start of the road to real digital system design flow.

The *Digital Electronics* course has the following major chapters [5]:

- *Introduction*
- *Logical Support for Digital Electronics*
- *Combinatorial Logic*
- *Sequential Logic*
- *Digital Integrated Circuit Design*

Each work place has a set of electronic apparatus Arbitrary Power Supply Unit, 15 MHz Arbitrary Function Generator, 150 MHz Mixed Signal CombiScope® with FFT [12].

For fast prototyping, a Digilent [11] Spartan 3E Starter Board (Xilinx Spartan 3E500) is used. The FPGA project is implemented using the free software ISE Webpack from Xilinx [15].

For the "hardware" part of the applications, a breadboard from Rapid [14] is used for wiring integrated circuit.

A logic analyzer (PC instrument connected via an USB port) is used for multiple digital signal investigation [13].

4.2. Lab Logistics and Recommendations

The lab applications take place in a dedicated lab room. The subject is mandatory for all registered students. A team of maximum 4 students shares the same workplace. There are 4 workplaces available in the same time.

The students must read and prepare in advance the theoretical and practical aspects of the lab. At the beginning of each lab, the tutor tests students' knowledge using few simple questions based on the current subject. These tests have a 20% contribution to the final evaluation.

The tutor makes a brief presentation of the current lab application requirements and flow.

During the lab, the students are asked to take notes, draw signal shape, draw circuit and produce table of measurements. This activity has a 60% contribution to the final evaluation. The tutor evaluates both team work and the individual contribution. During the lab session, the tutor interacts with each student for support and evaluation.

At the end of the semester, a final assignment is organized. The subjects are related to the practical aspects of the lab and counts for the rest of 20% of the evaluation.

The seven lab applications are run during a 14 weeks term, according to the schedule presented by Table 1.

Table 1

Weekly Lab Application Subjects

Week	Subject	Lab
1	Introduction.	
2	Lab Equipment. Digital Signals Measurement.	*Lab 1*
3, 4	Digital Signals Measurement (exercises).	*Lab 2*
5, 6	Digital gates. Digital Signals Measurement.	*Lab 3*
7	Xilinx ISE Design Flow. Schematic Capture. Logic Gates.	*Lab 4*
8	Schematic Capture. Combinatorial Logic.	*Lab 5*
9	Decoders. Multiplexers.	*Lab 6*
10, 11	Flip-flops.	*Lab 7*
12, 13	Evaluation Preparation.	
14	Final Assignment.	

5. Lab Content

Each lab is accompanied by a textual description that contains:

- Lab application objective;
- A brief theory reminder related to the current topic of the lab application;
- Step-by-step practical requirements;
- Questions and engineering problems.

Lab 1: *Electronic Lab Equipment. Digital Signal Parameters*

The first lab application introduces the equipment used during the rest of the term. Arbitrary Power Supply Unit, Arbitrary

Function Generator and Mixed Signal Oscilloscope are presented including the features, the front panel description and the operating modes.

It is presented also in details how to measure voltages, time, rising/falling edge, delay time between two signals using oscilloscope.

Figure 2 presents how to prepare the waveform for a correct measurement of the propagation time through an AND gate.

The major purpose of the lab application is to teach students how to make use of digital and analog oscilloscope for digital signal investigation.

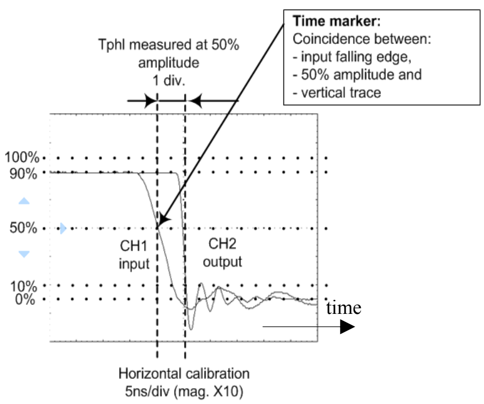

Fig. 2. *Waveforms preparation for propagation time measurement between input and output of an AND gate*

Lab 2: *Measuring Digital Signals*

The second lab application emphasizes on getting confidence in using electronic equipment. The focus is on measuring digital signal parameters, time and voltages, and evaluate the measurement errors.

The lab presents also how a passive RC circuit induces timing processing for electric signals. It is compared how the digital signal shape is modified versus a sinusoidal signal.

Figure 3a presents the case of a RC integration circuit and Figure 3b presents the case of a RC derivation circuit.

Lab 3: *Individual Logic Gates. Measuring Digital Signals*

The 3rd lab application introduces logic gates and make a comparison between TTL and CMOS gates features.

The students are requested to study the TTL inverter 7404 measuring the inverter timing parameters: rising time, falling time, propagation time. For propagation time measuring, two methods are suggested:

a) measure the propagation time through a chain of 6 inverters and

b) measure the propagation time with a four fan-out (FO = 4).

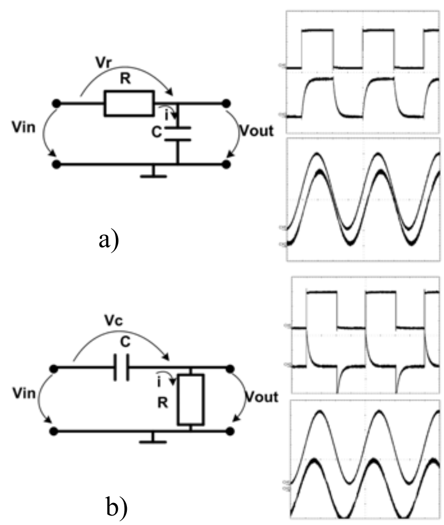

Fig. 3. *RC integration (a) and RC derivation (b) circuits and waveforms for digital and sinusoidal signals*

As an application for inverters, the students are asked to study the behavior of an odd/even number of chained inverters. It is expected to see that 3/5 chained inverters oscillate and 2/4/6 chained inverters present two stable states.

As an alternative, a CMOS NOR2 gate is studied under the same conditions.

For 2nd and 3rd lab a prototype bread-board similar to the one presented in Figure 4 is used.

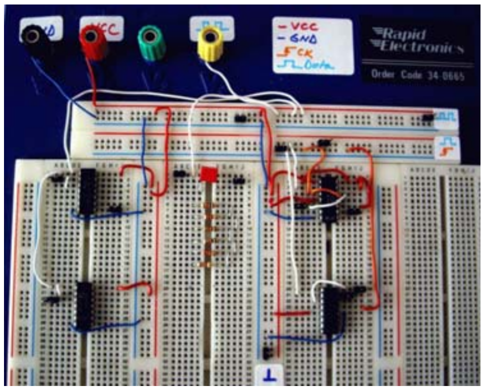

Fig. 4. *Prototype breadboard for investigating RC circuits (lab2), logic gates (lab3) and flip-flops (lab 7)*

Lab 4: *Xilinx ISE Design Flow. Schematic Capture. Logic Gates*

The 4th lab application introduces a new approach: implementing a simple logic circuit on a programmable device starting from a schematic or a HDL model. The prototype board is a Digilent Xilinx Spartan 3E Starter Board. Free software Xilinx ISE (Integrated Software Environment) Webpack is used for schematic capture and design implementation.

The theoretical part of the lab presents a tutorial about how to operate Xilinx ISE, emphasizing on schematic capture for a simple combinatorial logic. As an alternative, the students have access to the source files (project definition, schematic, constrains etc.) from the lab web-site. It is presented the whole design flow from the idea to the bit-stream used to program the device (schematic capture, synthesis, implementation, generating programming file).

At the end, the students are required to re-run the design flow and to implement a different logic function. The inputs are mapped to switches and the outputs are mapped to LEDs.

The students are encouraged to continue these exercises by themselves at their own places or at the laboratory, using similar FPGA board and the free development software.

Lab 5: *Schematic Capture. Combinatorial Logic*

The 5th lab exercises the design flow for programmable logic implementation and make use of the oscilloscope and the logic analyzer for investigating a digital system. As a case study, two simple logic functions are proposed (two and three inputs each). The students are required to minimize the functions, to draw the schematic and to run the FPGA flow. The input and output signals are observed on the oscilloscope display. The lab oscilloscope has 4 inputs, 2 analog and 2 digital inputs. During the lab, the students will discover how to make use of oscilloscope feature to build a graphical representation of four signals simultaneously.

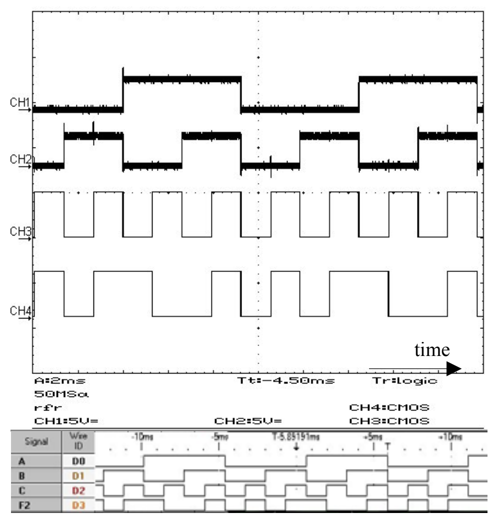

Fig. 5. *Analog/digital oscilloscope and logic analyzer displaying the waveforms for a three input logic function*

During the same lab, the logic analyzer is introduced. Using the logic analyzer, connected as an USB device, the students can investigate multiple signals (inputs and outputs) on the same waveform display. Figure 5 presents the waveforms obtained on analog/digital oscilloscope and corresponding waveforms obtained on logic analyzer.

There are few advantages presenting waveforms both on oscilloscope and logic analyzer. First, one can see the difference between a "digital signal representation" and its real analog shape. Second, one can see that the shape presented by oscilloscope is not identical with the one presented by the logic analyzer for the same input signal. For both oscilloscope and logic analyzer a user must correctly set trigger parameters (proper signal, level, edge, logic conditions).

Lab 6: *Decoders. Multiplexers. Adders*

The 6th lab application does not introduce any new noun but it focuses on consolidating student knowledge:

- Xilinx FPGA ISE design flow;
- Digital signal display on oscilloscope and logic analyzer.

The subject of the lab is related to decoders, multiplexers and adders. After this lab, students are expected to have the knowledge to implement a combinatorial circuit on a prototype FPGA board.

Lab 7: *Flip-flops*

The elementary sequential circuits are studied using discrete integrated circuits. Two sequential circuits are compared: D-latch 7475 and D-flip-flop 7474.

Using a prototype breadboard similar to the one presented in Figure 4, students interconnect by themselves a D-latch and a D-flip-flop. In order to drive these circuits with the same set of complex stimuli, a signal generator is implemented on FPGA (as a "black-box"). Students receive just a bit-stream to program the FPGA as a stimulus generator and make proper interconnection between FPGA and devices under test (7474 and 7475).

Figure 6 presents the studied configuration and the obtained output waveforms from latch and flip-flop.

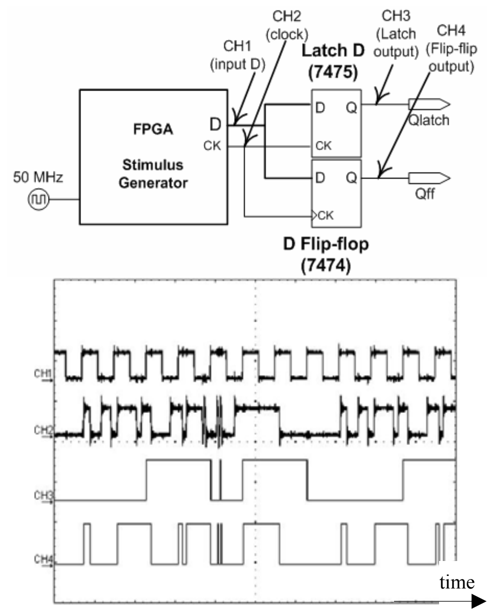

Fig. 6. *Latch/Flip-flop study: circuit and waveforms*

6. Results and Discussions

Student evaluation is done every week and at the end of the term, according to the Table 2.

Lab Activity Evaluation Table 2

Prtg	Subject Evaluated	When
20%	Testing the knowledge about the current lab application (theoretical and practical)	*At the beginning of each lab work*
60%	Personal contribution and skills.	*During the practical work*
20%	Practical hand-on assignment, related to the lab.	*Final Assignment*

The lab applications were run in the same semester for three specializations:

Electronics, Computers, Telecommunication. The results are compared in the Figure 7.

The lab is scheduled in the second term of the 2nd year of studies. Up to this stage, the students follow similar courses and have similar professional experience. The three specializations were presented just to have some comparison between groups and also to evaluate the subjective factor of the tutors.

Table 3 presents some relevant statistical data. Studying the results, some conclusion can be drawn:

- A big number of students in Electronics (30%) did not attend the final assignment. The evaluation is slightly sensitive to the tutor experience and expectation. The average for Telecommunication is 2 points higher compared to the other two specializations. At Computers, the shape of the marks distribution is a reversed Gauss curve.

- The distributions for Computers and Telecommunication present two maximum at the extreme evaluation (10 or 4).

- This can suggest that the tutor tends to evaluate as a "pass or fail" exam. The percentage of extreme evaluation are 54.5% and 64.2% much higher the same percentage at Electronics (18.4%).

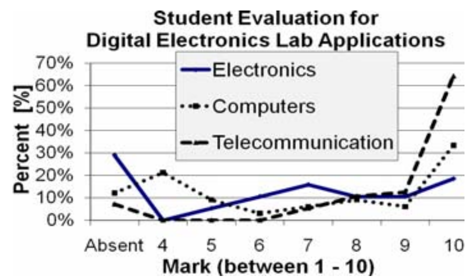

Fig. 7. *Student evaluation results for three different specializations* (*Electronics, Computer Science, Telecommunication*)

A student survey was conducted including various questions. The opinions were compared with those obtain from the previous generations of students.

The collected answers, suggest the following conclusion:

- Students enjoyed more the "abstract" lab applications (FPGA implementation) because they use a PC, they have a digital system ready fast and they are not exposed to too many physical details.

Statistical Data Table 3

	Electronics	**Computers**	**Telecommunication**	**TOTAL**	**Overall Percentage %**
Number of Students	38	33	56	127	
No. students PASSED	27	22	52	101	79.5%
No. students FAILED	0	7	0	7	5.5%
No. students marked with maximum (10)	7	11	36	54	42.5%
No. students ABSENT	11	4	4	19	15.0%
Average mark (maximum 10)	7.93	7.41	9.46	8.53	
No. students EXTREME (10 or 4)	7	18	36	61	
Percentage of students extreme marks	18.4%	54.5%	64.2%	48.0%	

- Students are not very excited by wiring parts and using electronic equipment for investigating signals (oscilloscope, logic analyzer).

7. Conclusion

This paper presents a new set of lab application for Digital Electronics course. The objective of the change was to update the lab topic to the current development in the field, including programmable device and blending learning approach.

From a teacher's point of view, the changes have required a complete revisited teaching materials and preparation of entirely new set of applications.

From the students' point of view it was observed that they were excited about having a "fast prototype environment" for building a small digital system. FPGA design flow was enjoyed by students. During a lab class they were able to build a simple digital system and to display meaningful signals on oscilloscope or logic analyzer.

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