A Recent Survey of Circuit Design Tools for Teaching

A. Alasdoon, *Member IEEE*, P.W.C. Prasad, *Senior Member IEEE*, A. Beg, *Member IEEE*, A. Chan, *Member IEEE*

Abstract— **Digital design is an essential topic in the computer science curriculum. A major problem in teaching digital design in computer architecture and organization courses is how to help students connect their theoretical knowledge with the practical experience. Many useful computer programs are available that can help overcome this issue and can cover various aspects of digital logic design. The programs range from simple simulators to specific teaching tools to advanced and specialized software. This paper presents a recent survey of such design tools that can be used for teaching purposes.**

***Index Terms*; Digital Systems, Digital Logic, Simulator, Hardware Trainer Kit**

I. Introduction

Computer organization and computer architecture are very closely related. Computer organization focuses on how operational attributes are linked together and contributes to realize the architectural specifications, where computer architecture focuses on the architectural attributes like physical address memory, CPU and how they should be made and made to coordinate with each other keeping the computing demands and goals in mind. Computer architecture is a major subject taught in undergraduate computer engineering, computer science and electronic and electrical engineering courses [1]. In many universities, computer architecture subject builds upon foundations taught in a computer organization course.

Computer organization and architecture involves many abstract concepts for the undergraduate beginner. Today, most students start undergraduate courses having already had contact with computers as users, which was hardly true some two decades ago. In this way, they see the computer in a preconceived way, as a tool useful for tasks such as Internet browsing or text-messaging.

Teaching these courses for computer science, computer engineering, and electrical engineering students in a conventional way is inefficient and insufficient if the teaching methods focus only on the theoretical aspects [1], [2]. A major problem in teaching computer architecture and organization courses is how to help students make the reasoning that connects their theoretical knowledge with practical experience [3], [4].

In general, students learn best when they take an active role in their learning. Students who sit passively in lecture courses, often not paying attention to what is being taught, will have great difficulty learning the material [5]. On the other hand, students who take a more active role in their education stand a better chance of learning the material and receiving higher grades in their courses. Therefore these courses are usually organized in such a way that students obtain not only a purely theoretical experience, but also a practical understanding of the topics lectured [4].

Digital design is an essential course in the computer science curriculum and the computer science/computer engineering students get familiar with digital systems much earlier than electrical engineering students get [6]. Though it is considered more of an electrical engineering discipline, digital design is critical for computer engineering and computer science students. It gives the basic theories, knowledge and experiment skills of digital electronic techniques and computer logic circuit design, which will be the basic foundation for understanding of the key concept behind the computer organization and architecture. However, challenges remain in teaching this subject effectively to computer science students [5], [6].

This paper explores the tools used to teach the digital systems in the higher education sector. The remainder of this paper is organized as follows. Section 2 summarizes the importance of digital logic in computer organization/ architecture courses and the issues in teaching digital systems in the classroom environment. Section 3 provides the survey results on the currently used teaching methods: use of hardware logic trainer / software simulators and advantages and disadvantages of those systems. Section 4 briefly explores some of the widely used simulation tools for teaching purposes. Finally, section 5 concludes the paper with the recommendations, and possible new techniques can be adopted for better outcome of teaching digital system courses.

II. Importance of Teaching Digital Logic in Computer Courses

Undergraduate digital logic design courses cover the basic building blocks of digital systems, including optimal

Dr. Abeer Alsadoon is a Lecturer with Charles Sturt University, Study Centre Sydney, Australia. (e-mail: AAlsadoon@studygroup.com)
Dr. Chandana Prasad Withana is a Senior Lecturer with Charles Sturt University, Study Centre Sydney, Australia. (e-mail: cwithana@studygroup.com)
Dr. Azam Beg is an Associate Professor with the College of Information Technology, University of Arab Emirates, Al Ain, UAE. (e-mail: abeg@uaeu.ac.ae)
Anthony Chan is a Lecturer with Charles Sturt University, Wagga Wagga campus, Australia.(email: achan@csu.edu.au)

implementation of logic functions, different logical number systems, arithmetic operations and circuits, combinational circuits, flip-flops, registers, counters, and synchronous sequential circuits [5]-[9]. The much broader coverage will be on the variables, functions and truth tables as well as the types and operation principles of the digital logic gates such as AND, OR, INV, and 7400-series logic chip circuits. The Boolean algebra is a fundamental topic that is used to simplify the logic expressions and to analyze the combinational logic circuits [7]. With the above basic knowledge the topics of read-only memory (ROM), programmable logic arrays, some practical components such as encoders, decoders, multiplexers and the operation of latches, e.g., flip-flops, shift registers, counters and the general sequential circuit timing diagrams and synthesis were covered [8].

There are two quite different ways of approaching the teaching of digital systems – the one employed in electrical and/or electronic engineering, and that of computer science and/or computer engineering [9].

The study of digital circuits and systems principles and techniques comes very often late in the curriculum as a special case behavior [9]-[11]. In this way, electrical engineers are usually strongly aware of physical consequences of designing digital circuits, like clock distribution problems and timing constraints. On the other hand, computer science/computer engineering students get familiar with digital systems much earlier than electrical engineering students get. They employ abstract models from Boolean algebra as a basis, instead of circuit theory models [10].

Digital systems have become increasingly common in recent years. This fact accompanied by ever growing complexity of contemporary digital systems puts the new and stringent requirements on the education in this field [11].

Teaching digital systems and logic is a complex task faced by the university lecturers. In general the lecturers pass the subject knowledge use of by course materials and students' notes, which are in a "lifeless" form. To get this task complete, the students visit the lecturers, make notes and have some tutorial tasks performed. The motivation to learn from such material or method may not be so high. Especially when teaching the concepts behind the digital systems, students should have the possibility of seeing the outcomes of the scenario based on the changes they make [11]. Without visually seeing those, it will be hard for the undergraduate students to acquire the required knowledge on the subject.

With the ever-increasing and changing technology, the digital circuit problems have become more complicated and complex, requiring creative thinking and skilled engineers to solve these problems. A number of teaching paradigms have been utilized to increase the student learning effectiveness for advanced and complex engineering problems. The studies have indicated that student learning experience can be improved when it is supported with hands-on laboratory components, practical applications and theoretical concepts covered in classrooms.

One of the proven approaches is "learning by doing" approach which allows students to grasp the knowledge by doing the experiment by themselves. This method allows students to experiment with different scenarios and learn how the concepts are applicable for each case.

III. Currently Used Teaching Methods

Providing the all-important practical exposure can be achieved using two different methods, which are hard-wired "kits" and simulator [6]. These physical kits generally consist of breadboard module to plug in the 7400 series Integrated circuits, power supply unit, analog and digital pulse generator, switches and the display unit. The simulator can be either PC-based using a programmable logic device (software and hardware) or virtual process (software only) [11].

The traditional approach is to use the bread-boarding and discrete logic gates to implement designs of concepts that come up during lectures. This process generally begins with a qualitative description of the behavior of the underlying circuit and then evolves to take on quantitative characteristics as a student develops truth tables for the circuit or as the output function for the given scenario. Then students construct the un-simplified circuit and check the output for the desired input variations. As a further improvement to the circuit, the circuit minimization techniques are applied manually to reduce the size of the circuit. In undergraduate level students will use the theoretical knowledge gained in Karnaugh maps to simplify the circuit. Finally the simplified circuit output is checked with the earlier output to justify that the simplification process is correct [7].

Luckily these basic digital circuits require low voltages and amperages to operate, but this does not reduce the concern for safety. These boards have are equipped with short circuit protection to ensure both safety for the user and the product in the event of a short circuit. The board also has the power supply uses components with internal short circuit protection. The power shuts down before damage can be done to either the user or device. Its important to make sure no shock hazard is present to the user with open terminals on the breadboard.

On the other hand, a digital logic simulator is firstly used to enable students to visually monitor and analyze the behavior of the switching circuits introduced through lectures, and secondly to help them design switching circuits and simulate them. The digital logic simulator is used for designing digital circuits and for performing visual simulations [2]. Basic building blocks and modules are available for making complex components and larger systems. A module once created can be used for designing other more complex modules. In addition to that, modification can be also made to any module [11].

The main advantage of the simulators is that the students can build and simulate basic logic circuits with just a few mouse clicks, drag components into the editor and then draw connections between them [5], [7]. It is easy to zoom, pan, and rotate as well. The most important feature is that when they finished designing their circuit, they can save it to their hard drive and try to simulate it any number of times until they are clear with the concept used for that experiment.

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The simulation is carried out interactively one or multiple number of events forward. During simulation a user can navigate through components, examine values of signals, and draw the timing diagrams. The simulation can be executed in a concurrent and distributed environment, enabling user to perform simulation of complex digital systems. [10]-[12]. Simulators are great for homework assignments and lab activities, where they could be run in real time, be paused, or be advanced step by step.

All the above-mentioned simulator-types can be categorized as commercial versus non-commercial tools. Though the commercial tools have more capabilities and use advanced feature, they are not the best to use for teaching purposes. Several authors state that the commercial tools have lot of disadvantages for the students, mainly because they are designed for commercial purposes and for the professional market; they may not have basic functions required for students to complete the task and might result in students getting confused [11]. On the other hand, somebody might argue that these commercial tools have more features for students to build their skills on digital circuits. However, uses of these commercially available tools suffer from high cost in terms of software and hardware.

Many excellent hardware simulators and tools have been developed by the academics for teaching digital logic and computer hardware, and a number of them are freely available and widely used [12], [13]. Table 1 illustrates number of simulator types found in this survey. It's hard to find fully fledge simulators only design for digital logic circuits, however most of these simulators work for different type of digital circuits.

Table 1. Availability of simulators

SIMULATION TYPE	**Count**
Transistors/Components	11
Gates	18
HDL (VHDL/Verilog/SystemC, etc.)	12
Architecture/System	36
Circuit Synthesis	11
Layout (Chip/PCB/None)	12
Total	100

IV. DETAILS OF SELECTED SIMULATORS

This section reviews a few simulators suitable for teaching digital logic courses in computer architecture and organization [12]. The basic characteristics and features of selected simulators are given, which include target users, operating systems on which the simulators run, programming languages used for their development, special features and some screen shots of the interface used. The detailed descriptions are not given in the paper for reasons of length. In order to provide readers with the complete features of these simulators, more data are given in [13]-[17].

A. *Hamburg Design System* (HADES)

Hamburg Design System (HADES) is a simulation tool that has been developed by Computer Science Department, Hamburg University, and it depends on Java framework. HADES' components are a graphics editor to create and act upon simulation setups, self-generated design and library browser, and simulation model of JavaBeans library. Most of simulation components that are provided by this tool are used for digital circuits that range from basic gates to register transfer level design, and from basic input/output to system level components [14].

The tool provides a fully-interactive simulation environment. Through its graphics editor the students can edit their circuits and apply parameters or fixing any circuit problems at the same time as the simulation is running. It is advantageous to fix the detected problem directly and to show the corrected results. This tool can be used for teaching basic digital system design and for research on system simulations and hardware/software co-simulation. The following Figure 1 illustrates NAND-based JK flip-flop circuit constructed using this simulator.

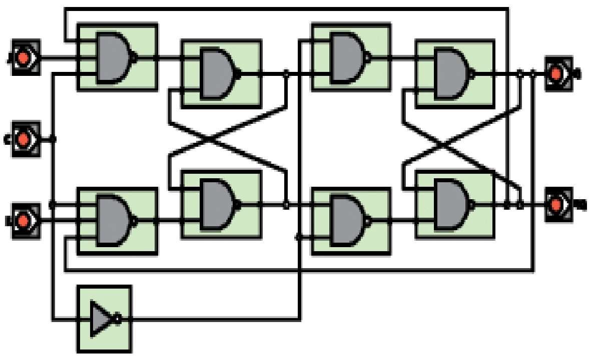

Fig. 1. A sample HADES schematic

B. *LabVIEW*

LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) is a commercial simulation tool from National Instruments and depends on their visual programming language. LabVIEW simulation is an effective visualization tool used in digital logic teaching. The tool can demonstrate the students' participation, and increase the strength of the design and practice of self-created experiments. LabVIEW's block diagrams include different *function*-nodes. A student connects these nodes by drawing wires. A function-node can be implemented as soon as all input data become available. This kind of simulation makes use of all types of Boolean controls as shown in Figure 2. In addition, the tool provides completely functional logic operator as shown in Figure 3.

This simulator has the ability of parallel processing that implements multiple function-nodes concurrently. Multi-processing hardware multiplexes different operating system threads when the function-nodes ready for implementation [15].

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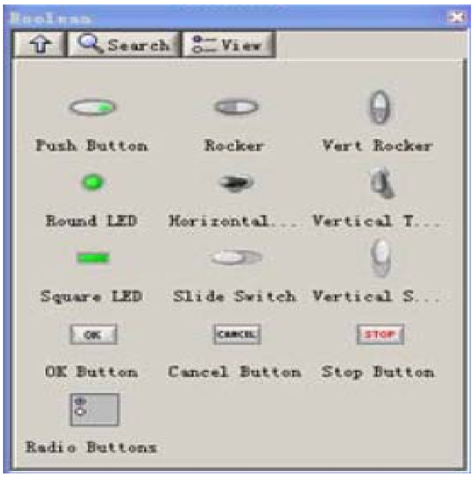

Fig. 3. LabVIEW's controls

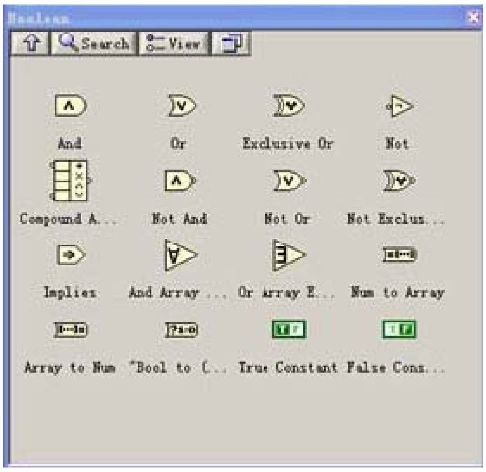

Fig. 4. LabVIEW's functions

C. *Logisim*

Logisim is a simulation tool developed by Carl Burch from Hendrix College, USA, and depends on Java programming language. It used by students in different institutes and universities around the world in different ways, starting from basic units in logic circuit courses to computer organization and architecture courses [16].

The tool has simple interface that facilitates the learning process. The tool interface has color-coded wires that are used in drawing and simulation. Horizontal and vertical wires are drawn and automatically connected to other function-nodes and to other wires. Figure 4 presents a sample schematic drawn in Logisim. Logisim can be used to simulate small simple logic circuit and to build from modules from the circuits. Then these modules can be used to build large complex logic circuit. This tool can help students in designing and simulating larger circuits such as a CPU.

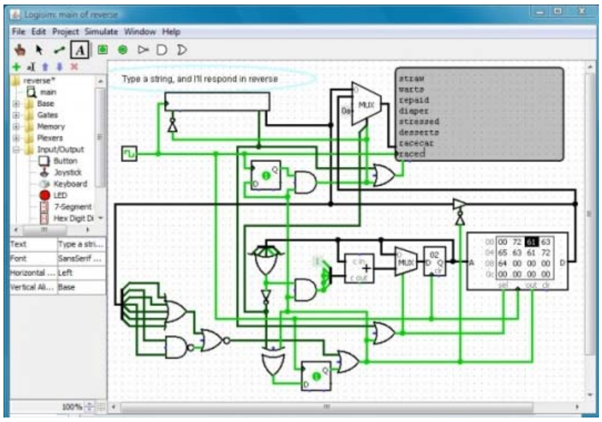

Fig. 2. A schematic in LogiSim

V. Conclusions

Digital logic is one of the key knowledge areas in computer architecture and organization specialization. Due to the complexity in the subject, delivery method should include not only lecture classes but also practical work using simulators. This paper surveyed a range of such simulators available in the market and evaluated simulators freely available and suitable for laboratory use. The strategy adapted in the study discussed the usability, affordability, availability and the course contents covered by different simulators before inducting them into the experimental work. The future work includes analysis of much larger number of simulators based on specific characteristics. This will be achieved by adopting laboratory work using some of the freely available simulators for teaching digital courses in different universities and by evaluating on the knowledge grasped by students from the use of those simulators, and then by comparing the past results of students when there was no laboratory work conducted. This will justify the significant difference in the behavior of the students' learning process.

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