Expand the pipeline: K-12 curriculum development on VHDL and FPGA design

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Abstract

Because every electronic system manufactured today has an embedded "brain" comprised of reconfigurable electronics components, there is an overwhelming national need for technicians who are trained in reconfigurable electronics systems. The movement to reconfigurable digital systems using Field Programmable Gate Arrays (FPGAs) and microcontrollers is sweeping the electronics world in the rush to create smaller, faster, and more flexible consumer and industrial devices. Today, a more standard development process for Digital Logic Design is widely used in industry. The process uses Very High Speed Integrated Circuit Hardware Description Languages (VHDL) as a design entry to describe the digital systems. Responding to this need, Drake State Community College and its partner institutions proposed to utilize highly-qualified academic and industry-experienced resources to develop and deliver curriculum, professional development, and outreach activities that will draw high school students into electrical engineering technology programs, this will expand the number and diversity of highly-skilled workers for the targeted industries and accelerate the introduction of qualified workers into the pool of skilled technicians needed by electronics firms. This pool of highly-skilled technicians will be built and sustained by strengthening and expanding community college and university partnerships with K-12 systems, affiliate community colleges, and established industry partners. This paper will discuss the development of the digital systems curriculum module that can easily be integrated into existing high school technology courses having electrical/electronic content. One goal of this project is to provide resources that will assist high school curriculum coordinators in linking this module to high school technology curriculum. The course emphasizes on digital logic circuits. Number systems, codes, Boolean algebra, logic gates, combinational logic, sequential logic circuits. Students will become familiar with the basic digital systems and develop skills in digital design using VHDL and FPGA.

I. Introduction

Technologists trained on modern reconfigurable electronics will change the way digital logic systems are designed and delivered. Modern digital electronic design has changed very significantly over the last decade, making schematic design largely a thing of the past. Recently, the complexity of circuitry has grown to hundreds of millions or even billions of transistors in a single chip. As a results, computer-aided design has become the industry standard for entering, evaluating, and testing designs. These technologies have become closely coupled with new "reconfigurable" electronic devices that include Field Programmable Gate Arrays (FPGAs), microprocessors, and advanced microcontrollers. Virtually every electronic system created today uses at least one of these new devices, from large automotive and energy equipment to small, hand-held, medical devices and everyday household items. Without a doubt, tomorrow's technicians must understand the nature of modern digital design.

According to the Bureau of Labor Statistics (BLS) the replacement rate in science, technology, engineering, and mathematics (STEM) occupations over the decade 2008-18 is projected to be very demanding [1]. For instance, the projected replacement rate in mathematical science is 29.5%, in physics is 28.5%, in mechanical engineering is 26%, and in electrical engineering is

23%. According to data from the Current Population Survey [2], the share of the population aged 16 and over who have college degrees roughly doubled over the past three decades, as did the share of those with some college education. Over the same time, the share of those attaining a high school diploma or less declined. Employment of college graduates is projected to grow faster than average from 2006 to 2016 [2]. Increasing demand for technological advances means more jobs for STEM workers. More STEM workers also will be needed to replace those who are leaving these occupations. Many highly skilled workers will retire, change careers, or move to management positions over the next decade. Employers are expected to hire about 2.5 million STEM workers who are entering their occupation for the first time [3,4]. Along with near future high demand for a well-educated workforce, there is a growing concern that the United

The United States is not preparing a sufficient number of students, teachers, and professionals in STEM areas [5, 6, 7, 8]. In a recent international assessment of 15-year-old students, the U.S. ranked 28th in math literacy and 24th in science literacy. Moreover, the U.S. ranks 20th among all nations in the proportion of 24-year-olds who earn degrees in natural science or engineering [5]. In the National Academy of Sciences (NAS) report "Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future," as well as in the Administration's American Competitiveness Initiative [9], five distinguished recommendations targeted at improving STEM education were made. These five recommendations seek to increase the supply of new STEM teachers, improve the skills of current STEM teachers, enlarge the pre-collegiate pipeline, increase postsecondary degree attainment, and enhance support for graduate and early-career research [5].

There is general consensus among educators that students interested in a STEM career should get started in high school by taking as much math and science as they can. The more math and science students learn in high school, the easier it is to tackle advanced subjects later. Success in STEM requires both technical and nontechnical skills and attributes. Curiosity, the ability to think logically, and creative problem-solving are highly valuable. Due to globalization, communication skills and teamwork are "must have" skills. Preparation should begin in middle schools and continue through high school [3], with coursework and extracurricular activities focusing on honing problem-solving skills. It is our role as educators to provide the students with these valuable opportunities with the goal to motivate and engage students to pursue the STEM career pathways.

Because every electronic system manufactured today has an embedded "brain" comprised of reconfigurable electronics components, there is an overwhelming national need for technicians who are trained in reconfigurable electronics systems. Responding to this need, two community colleges and two university propose to utilize highly-qualified academic and industry-experienced resources to develop and implement online and technology-enabled courses and learning projects that will be scaled up to reach significant numbers of diverse instructors and students over a large geographic area. These collaborative efforts will satisfy this critical need for trained instructors and students in the technology of reconfigurable solutions. Additionally, the project will expand and improve the delivery of education and training material, and provide students and workshop participants with the critical skills sought by diverse electronics industries across the United States. Strategic partnerships in key geographic areas will help underrepresented and unemployed populations advance their skills and training to become eligible for high-wage, high-demand positions in reconfigurable electronics systems. The participating community colleges serve large minority populations (Hispanic, Native Americans, and African-American) in the Southwest and Southeast regions of the United States.

Major outreach activities will be de developed to provide high school/college dual enrollment to accelerate student progression, summer bridge programs to strengthen student interest in seeking STEM fields, summer institutes for enhancing the STEM teaching capabilities of secondary school educators, electronics career expos, and tours of electronics industries for secondary and postsecondary students and educators. Professional Development activities will provide secondary school instructors with the pedagogical and subject matter knowledge, digital teaching tools, and teaching strategies that will attract and effectively prepare students for STEM careers in reconfigurable electronics and other advanced electronics fields.

II. High School Digital System Curriculum Development

The University team developed a curriculum module to be incorporated into high school technology courses. The course emphasizes on digital logic circuits. Number systems, codes, Boolean algebra, logic gates, combinational logic, sequential logic circuits. Students will become familiar with the basic digital systems and develop skills in digital design using FPGA. Students should be able to:

1. Understand the basic logic gates and combinational logic functions, symbols, truth tables, timing diagrams, and logic circuits.
2. Simplify complex logic circuits by applying Boolean algebra laws and theorems
3. Understand the operation of basic counters, decoders, multiplexers and arithmetic circuits.
4. Convert between the decimal, binary, and hexadecimal number systems.
5. Understand binary, and BCD, and the need for alphanumeric codes, especially the ASCII code.
6. Perform binary addition, subtraction, multiplication, and division on binary (using the 2's-complement system) and hexadecimal numbers.
7. Understand the basic types of flip-flop.
8. Understand sequential logic systems including synchronous and asynchronous operation.
9. Use modern computer tools for digital design/verification using VHDL.
10. Understand the characteristics of modern programmable logic devices

Curriculum Modules:

Hands-on learning is infused into a sequence of instructional modules, each module has an associated laboratory exercise to enforce the learning experience of students. The curriculum is composed of eight modules to allow students to pick and choose components to match his/or her learning needs. All of the laboratory exercises are conducted using The Altera® Development and Education (DE2) board [10] which provides an ideal vehicle for learning about digital logic, computer organization, and FPGAs. The following is a description of each module, relevant topics that are covered and expected learning outcomes.

Module 1: Introduction to Quartus II Software Design Series
This introductory module describes FPGA as a new design platform for digital systems, it also provides extensive training on how to use Quartus® II development software to develop an FPGA or CPLD [10]. Students will be able able to create a new project, enter in new or existing design files, and compile their design. Students will learn how to plan and manage I/O assignments and apply timing analysis of design to achieve design goals using Quartus® II development software.

Module 2: Numbering Systems
This module introduces the basic concepts of logic circuits. Students will learn numbering systems, convert from one number system to its equivalent in one of the other number systems. Students will learn the difference between BCD and straight binary, and understand the purpose of the alphanumeric codes such as ASCII code. The corresponding lab is a 7 Segment Display, where has the students build, using schematic capture, a binary to BCD converter that displays the output on a 7-Segment display.

Module 3: Combinational Logic Circuits
This module introduces the basic logic gates and their algebraic and symbolic representations. Truth tables are introduced as a means of testing all input and output combinations. Numerous examples are given to help students work through on their own and test their understanding of the topics being discussed. The Boolean theorems are taught as well as DeMorgan's. The second part introduces combinational circuits and provides many more examples and real life applications of what the students were just taught. Converting between Sum-of-Products and Product-of-Sums representations are also taught as well as the specialty logic gates XOR and XNOR. The corresponding lab is a Voting Circuit, where students have to build an un-simplified version of a 2/3rds majority vote circuit. This lab is a good example to show how simplifying circuits can reduce the number of gates in a circuit, which in turn saves energy, and reduces costs and errors. The end of the lab contains a Post Lab that shows the simplified version of the circuit that the Quartus II software actually implements on the DE2 board.

Module 4: Sequential Circuits – Flip-Flops
This module introduces Flip-Flops as memory devices; student will learn the operation of a latch flip-flop and apply various timing parameters specified by the manufacturers. Students will understand the difference between synchronous and asynchronous systems; students will also learn Flip-Flop applications. State transition Diagrams are also briefly discussed.

Module 5: Digital Arithmetic circuits
This module covers basic principles that are necessary for understanding how digital systems perform basic arithmetic operations. Students will learn the actual logic circuits that perform the arithmetic operations in a digital systems, mainly parallel adder, subtractor, and Arithmetic Logic Unit (ALU). The corresponding labs are Combinational Logic Design (Full Adder) and Logic Design (Full Adder/Subtractor), where students start by building a 1 bit half adder, combining it to make a 2 bit full adder and then in Lab 5 make a 4 bit full adder/subtractor using an ALU.

Module 6: Introduction to VHDL

This module provides introduction to the VHDL language and its use in programmable logic design. Students will gain a basic understanding of VHDL. All the basics of VHDL are covered from structure, syntax, libraries, naming conventions, how to use behavioral modeling constructs and techniques to describe the logic functionality of basic logic circuits. The two corresponding labs are Counters and Counters VHDL, where the students build first a counter using schematic design. Then the second lab has them create the same circuit with VHDL code which is given in the lab handout. This code is commented with the explanations of what each line does so students can understand it and/or change it for future uses.

Module 7: Basic Logic Blocks

This module covers basic operations on digital data and describes the associated logic blocks such as multiplexers, de-multiplexers and decoders. Each topic is explained and more examples are shown and discussed showing the real world applications of such circuits. The corresponding lab is a 3 to 8 decoder where students have to build and test a decoder using schematic design. Additionally, students will build and test 4 bit 2x1 multiplexer circuit.

Module 8: Capstone Project

This module is a lab only module and acts as a capstone to the entire Digital System design course. This integrating experience develops student competencies in applying digital systems and FPGA technical skills in solving a design problem. It gives a good real-world application of what can be accomplished with FPGAs. There are two capstone laboratory experiences. The first is a lab that has students exercised a given design to code the Falling Sand Game. The second lab introduces the DE2 boards on board memory and the ability to be controlled over USB. Other functions can be controlled from the program as well such as the LED's, the LCD, the VGA port, the 7-seg displays and the PS2 port.

III. Implementation and Assessment

The first workshop for high school electronics and technology instructors will be implemented in summer 2014 at Drake State Community college, participants are faculty from the three primary feeder school systems. Assessment is a vital part of any curriculum development and helps provide useful information for workshop enhancements and determining if the workshop has met its objectives. Formative evaluation will occur during the workshop delivery and will be used to inform adjustments for subsequent workshop offerings. Embedded assessment will be used to measure each workshop objective and determine whether goals are met. Assessment of the effectiveness of the faculty workshops training sessions offered will be conducted anonymously using pre- and post-surveys. Assessment data will be collected, analyzed, and used in continuous improvement actions to be implemented in next offering. We will use a pre-test/post-test design and pre-survey/post-survey employing both direct and indirect measures of student learning. The indirect assessment instruments will also include questions regarding participants' satisfaction while direct assessment instrument will include a set small design problems and multiple choices problems.

IV. Outreach

The project objective is to increase enrollment in electrical engineering technology programs to create growth in the number of electronics technicians entering the workforce. Partner institutions are addressing their role toward this goal by developing and implementing outreach programs that will not only stimulate greater interest in secondary students seeking electronics technician careers but also in better preparing secondary students for successful entry into and retention and completion rates in electrical engineering technology programs at the postsecondary level. An outreach model has been developed, it is expected to result in growth of enrollment in electrical engineering technology programs. The model has three parts: (1) university articulation, (2) high school student outreach, and (3) high school curriculum and teaching enhancement. The project has developed and implemented activities to increase the number of high school students pursing career in electrical engineering technology, activities include Summer Bridge program, STEM Camp for Adult Learners, Enhanced Enrollment Services, and Ultimate Engineering Experience:

V. Conclusion

Investing in education, especially at early ages, plays a crucial role in the future economy. Educators have been making measurable progress to improve STEM education from K-12 to college and beyond, but challenges remain. Digital systems sit at the heart of the technologies that most enrapture the young. This paper discussed the development of the digital systems curriculum module that can easily be integrated into existing high school technology courses having electrical/electronic content. One goal of this project is to provide resources that will assist high school curriculum coordinators in linking this module to high school technology curriculum. Students will become familiar with the basic digital systems and develop skills in digital design using VHDL and FPGA.

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