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Work-in-Progress: Right out of the Gate: Supporting Applied Technology and Engineering Students in Inroductory Digital Logic Courses Using Logisim-Evolution and Basys 3

Jeritt Williams

Jeritt Williams is an Instructional Assistant Professor in the Department of Technology at Illinois State University where he teaches courses in Engineering Technology and Computer Systems Technology. Prior to joining the university faculty, Jeritt worked in manufacturing and logistics, taught Technology and Engineering Education at the middle and high school levels, and served as the coordinator for STEM education at Illinois State University's Center for Renewable Energy. His research interests include smart manufacturing education and interdisciplinary STEM education.

Jaby Mohammed (Assistant Professor)

Jaby Mohammed is an Assistant Professor of Technology at Illinois State University, where he teaches Data Analytics, Six Sigma, and Parametric modeling. After working with Khalifa University, Purdue University, and Morehead State University, Dr. Mohammed joined the technology department at Illinois State University. He worked as engineering faculty with Kentucky Governors Scholars Program from 2006-to 2012. Dr. Mohammed is a senior member of the Society of Manufacturing Engineers (SME) and the Institute of Industrial Engineers (IIE). His area of research includes New Product development, human factors, six sigma, and Lean Manufacturing. He has conducted applied research in laser cladding and rapid prototyping using DMD and SLS machines. Dr. Mohammed holds a Ph.D. in Industrial Engineering from the University of Louisville, an MBA in operations management, and his Bachelor’s in mechanical engineering from University of Kerala.

Work-in-Progress:

Right Out of the Gate: Supporting Applied Technology and Engineering Students in Introductory Digital Logic Courses Using Logisim-Evolution and Basys 3

Teachers in undergraduate programs often find it challenging to engage with students so that materials and knowledge related to the subject matter are communicated in an efficient and meaningful way. To address the effectiveness of knowledge transfer and to make the Digital Electronics (DE) classroom experience more productive, several pedagogical approaches such as active learning with a hands-on approach, scaffolding, project-based learning, authentic and real-world learning, simulation within the classroom environment, and teamwork have been found to be effective [1]-[4]. Additionally, recent advances in technological tools have created opportunities for a flexible curriculum that serves the needs of students, preserving the theory and basic principles of the DE course, while following current trends of industry [5]. This paper will discuss the work-in-progress development of a DE course, re-designed using Logisim-Evolution circuit simulation software and Basys 3 FPGA to address the learning outcomes of the DE course. Previous studies on the use of virtual platforms and integrated hardware have indicated that students respond well to solutions like Logisim-Evolution [6]. This work builds on similar studies that have used Logisim-Evolution software in parallel with the Nexus 2 FPGA and found that surveyed students felt that these tools increased their self-efficacy, provided a means for hands-on learning even in remote settings, and were effective options for developing debugging and troubleshooting skills [7].

DE can be an intimidating course for applied Engineering Technology (ET) and Computer System Technology (CST) students for a variety of reasons. For example, students from both majors reported that they did not see the relevance and connection to their major(s) and future career path. Additionally, many students reported that the course was more challenging than other courses on end-of-course evaluations, and overall grades were often reflective of these concerns. DE is required for CST majors and is an elective for ET students. The ET and CST programs have different expected program outcomes; however, the DE course is expected to address the goals of each program. To accommodate students from both programs, a focus on an introduction to digital logic has superseded the goal of learning the fundamentals of electronics.

Purpose

The purpose of this qualitative work-in-progress is to explore the development of a DE course that utilizes ubiquitous, affordable, and accessible, tools and practices to provide students with an authentic, hands-on approach to learning and are applicable and relatable to students' academic interests and future career plans.

Course Background

One section of DE with 20-24 students is offered each semester and is taught by the same instructor. The course typically consists of an even mix of CST and ET students. Prerequisites for the course include Finite Mathematics or demonstrated equivalent competencies and admission to either the CST or ET major, or by instructor consent. The major goals of the DE course are:

1. Identify essential elements, components, and features of digital circuits
2. Apply common formulas and theories in circuit analysis
3. Use binary, octal, and hexadecimal number systems
4. Use software to design working circuits
5. Develop circuits from Boolean expressions or truth tables
6. Describe characteristics and functions of logic gates, flip-flops, registers, and counters
7. Create and download programs to the development board, test, and debug
8. Design and evaluate embedded systems based on real-world applications

Course History

When the DE course was first offered in the mid-1990s, it was based largely on working with discrete electronics and circuit prototyping, resembling a stereotypical introductory DE course of the time. By the mid-2000s, the course introduced the use of Programmable Logic Devices (PLDs) that were programmed using computer software. Due to the prohibitive cost of materials and equipment compared with relatively low demand for their use, students were required to lease equipment from the department each semester. These funds would in turn be used to purchase replacement materials and upgraded equipment as needed. While prior programming experience is not required for the course, working with Hardware Description Language (VHDL) was necessary to utilize the boards, causing many students to express feelings of frustration and anxiety. The need for higher-level programming languages to aid in VHDL programming has been of previous concern to DE educators and is reflected in the various solutions that present students with familiar coding options as alternatives, for example [8]. These issues, coupled with innovative teaching and learning practices such as using simulation tools and personalized techniques implemented during the remote learning periods of the Covid-19 global health pandemic of 2020-21 further supported the need for redeveloping and revitalizing the DE course, resulting in the adoption of a new development board and circuit design software in the Fall of 2021.

Course Topical Outline

The following topics are covered in the DE course:

- DC Circuit Fundamentals
    - Identifying and Working with Common Components
    - Fundamentals of Schematics, Symbols, and Diagrams
    - Prototyping, Breadboarding, and Circuit Building Basics
    - Common Integrated Circuits
- Logic Gates/ Combinatorial Logic
    - Basic, Universal, and Alternative Gates
    - Truth Tables and Logic Expressions
- Number Systems and Conversions
    - Binary

  - Octal
  - Hexadecimal
- Simplification Methods
  - Boolean Expressions
  - Karnaugh Mapping
- Sequential Logic and Finite State Machines
  - Signal Timing
  - Flip-Flops, Registers, and Counters
- Embedded Circuit Applications and Projects
- Troubleshooting, Debugging, and Problem-Solving Techniques

Logisim-Evolution Software

Logisim-Evolution (https://github.com/logisim-evolution/logisim-evolution) is a free, open-source graphics-based design tool that that extends the work of Carl Burch's original Logisim software [9]. Logisim was actively developed from 2003-2011 and remains available today in archived form (http://www.cburch.com/logisim/). Burch's original Logisim (and many variants) have been purposeful as an educational tool because it offers a free, feature-rich alternative to software like MultiSim and others, whose goal is to provide circuit simulation, design, and testing capabilities. According to Burch's website, many educational institutions have used versions of Logisim over the years, including more than 75 colleges and universities in 30 U.S. states, and in many other countries worldwide. The Logisim-Evolution project has continued the tradition of open-source and is currently under active development as of the time of this writing. Several U.S. and international colleges and universities have contributed to the project, and many have created their own versions, known as project forks, that provide distinctive digital design features and simulation tools, such as the ability to work with computer architecture like RISC-V, for example [10].

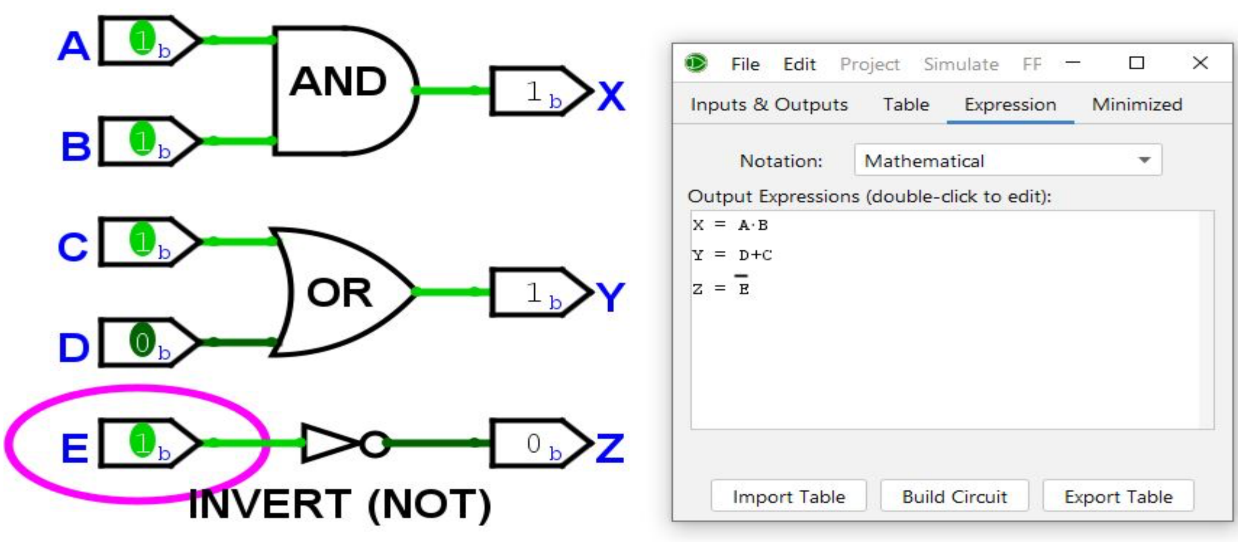

Figure 1. Logisim-Evolution is used to demonstrate and simulate operation of 'and-or-invert (AOI)' gates and corresponding mathematical expressions.

Logisim-Evolution is programmed with Java, and the code can be modified/ compiled by the user, or downloaded in a pre-compiled executable for Windows, Mac, or Linux, making it universally *accessible*. Since Logisim-Evolution is free of charge, it is *affordable*. The schematic symbols available to the user are based on industry standards, making them *ubiquitous* to electronics students and logic designers. (Fig. 1).

Basys 3 Hardware

The Basys 3 (Fig. 2) is an Artix-7 FPGA trainer board, produced by Diligent, a National Instruments company (https://digilent.com/shop/basys-3-artix-7-fpga-trainer-board-recommended-for-introductory-users/). The board is intended for development purposes and includes user-configurable switches, buttons, and LEDs (individual and seven-segment) that are pre-wired. Additionally, there are VGA, USB, and PMOD (Peripheral Module) ports that are compatible with a variety of off-the-shelf components such as an alphanumeric keypad or common digital or analog sensors. The layout of the Basys 3 is ideal for non-electrical engineering students, as it removes many of the "students as electricians" elements of working with electronics. Little to no wiring is required (outside of the use of certain PMODs) and power is typically handled via the USB cable, which is also used for sending the bitstream file to the board (downloading the program). Programs can be flashed to memory and the board can be run via an external power source if desired (i.e., can be used as part of a larger project).

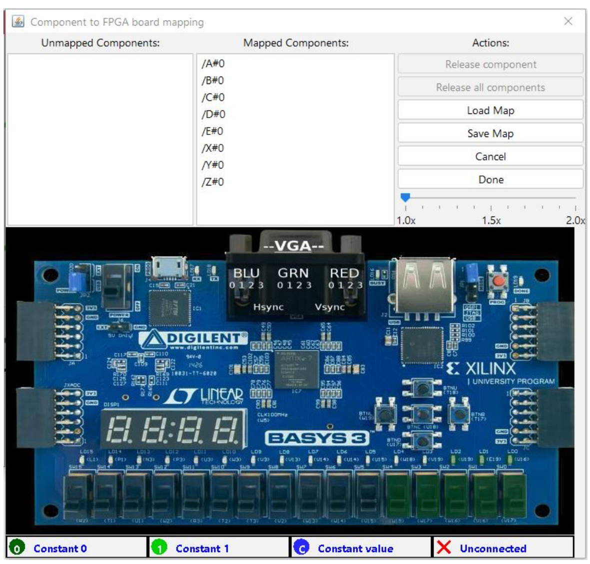

Figure 2. I/O pins used in simulation are mapped to Basys 3 hardware as user-selected, and the constraint file is automatically generated.

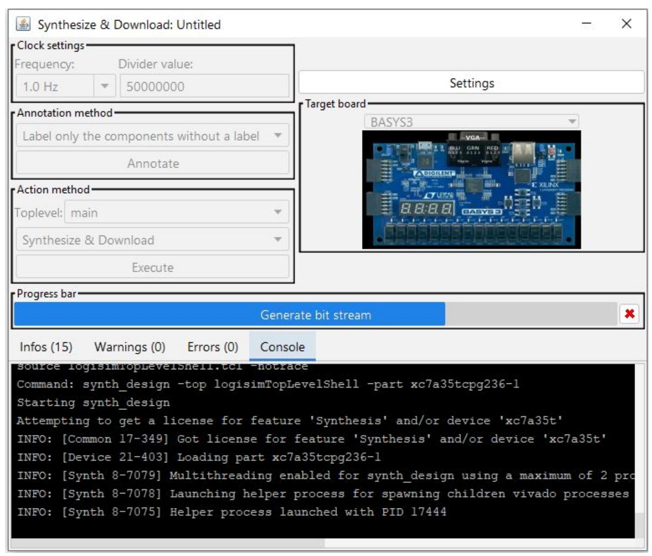

Figure 3. Synthesis, implementation, and bitstream generation is done via background script, eliminating the need for traditional Vivado workflow.

The Basys 3 FPGA board must be programmed using Xilinx tools. While the primary software for completing this task directly is Vivado Design Suite, Logisim-Evolution can communicate with the Basys 3 indirectly using scripts that generate HDL code and hardware mapping constraints files, conduct the synthesis, implementation, and bitstream generation (and downloading to the board). These scripts run in the background without the need to open Vivado.

Reducing or eliminating the traditional Vivado workflow saved many students time and the frustration of troubleshooting unknown and obscure errors, allowing them to focus more on designing and debugging logic versus resolving syntax errors, etc. (Fig. 3).

Implementation

Each student was issued a Basys 3 development board. At the time of this writing, the Basys 3's retail price was USD$149 and offered an educational discount of 25%, resulting in a total price of $111.75 per unit, making the cost to implement in a laboratory setting or for individual students quite reasonable, especially when comparing it to other boards with similar capabilities.

The Fall 2021 semester began by using Logisim (legacy version) to introduce logic fundamentals, then transitioned to using Vivado to implement designs on real hardware. Students had no prior experience working with Verilog (or VHDL) HDL coding and many were novice programmers in any language, so many activities focused on the basics of programming. The fundamentals of logic were introduced simultaneously, resulting in what appeared to overload and overwhelm many students. Initially, students were enthusiastic about the capabilities of the Basys 3 but interested quickly waned as students struggled with Verilog HDL and the complexity of using a comprehensive development environment like Vivado Design Suite. While some learning materials and tutorials were made available by Xilinx, lack of recent updates and scarcity of novice-level materials discouraged many students and frustrated the instructor.

Towards the middle of the Fall term, the instructor had discovered Logisim-Evolution. It was a matter of coincidence that Logisim-Evolution included the ability to not only interact with FPGA's but had been made compatible specifically with the Basys 3 and now supported Verilog (in addition to VHDL), which was the language that students had already become familiar with. Due to a variety of factors, including pandemic-related absences and inability to complete coursework outside of the lab, course progress slowed, and it became necessary to review and reintroduce concepts multiple times, adjust the course schedule, and cut out critical content from the course. This signaled a need for change. The decision was made to pivot to a new teaching and learning approach: Using the Basys3 and Logisim-Evolution, foregoing Vivado.

Outcomes

The instructional transition to the new course structure was smooth. Productivity increased and students exhibited fewer signs of being overwhelmed. When asked to rate the course "as an excellent course", overall ratings were positive. Qualitative feedback suggested a positive attitude towards the course and relevance towards career goals. Comments included: "I thought this class prepared me well for real world applications", "I felt that the flow of the class, from introducing core ideas to implementing them in the final project was smooth and made sense in the order presented", and "the topics were all things that are currently being used in the field of technology, and I feel like I learned a lot." Students were able to complete multiple projects that were designed in Logisim-Evolution and implemented on Basys 3, such as design of a reprogrammable digital safe. (Fig. 4).

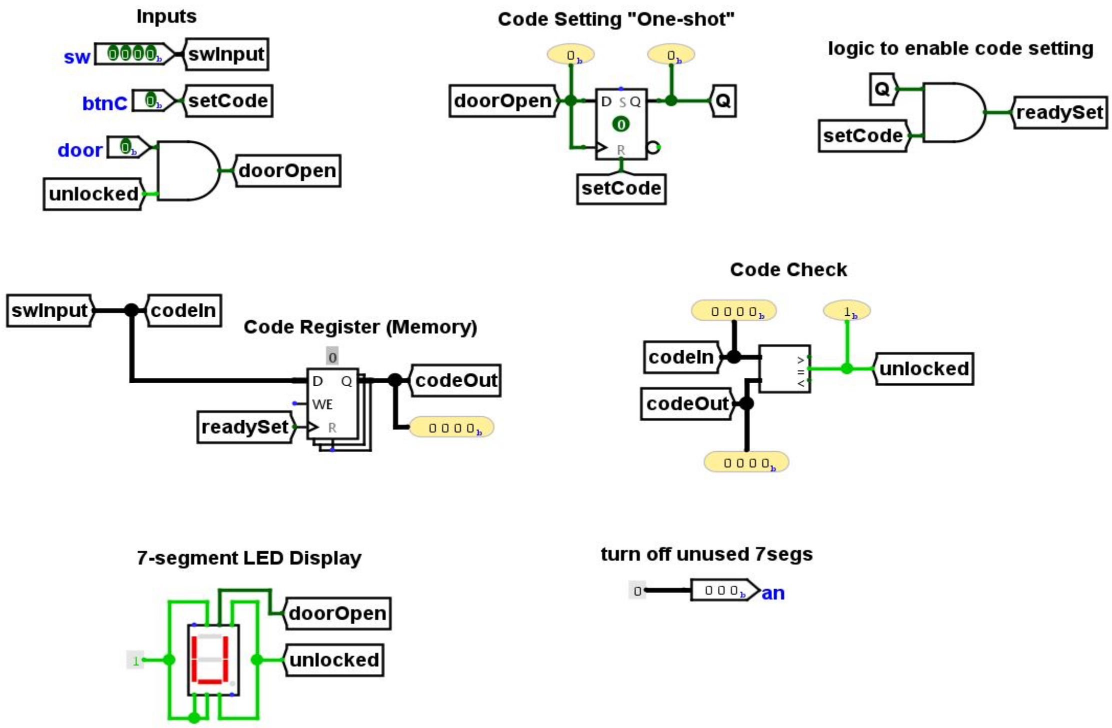

Figure 4. Example Student Project: Reprogrammable Digital Safe

Assumptions and Limitations

The DE course is under active redesign, and the findings presented in this paper are based on early observations that are subject to further investigation. Logisim-Evolution is under active development and bugs are regularly encountered. This could be problematic for students who are still learning the basics and cannot recognize when a bug is present versus an error in their own solution. Furthermore, the ability to utilize all functionality of an FPGA board is not yet present via Logisim-Evolution. In many cases it would not make sense or be efficient to program the board using only limited drag-and-drop style CAD-based tools. For example, creating a clock divider circuit in Logisim with more than a few flip-flops would be cumbersome and time consuming, whereas creating the same logic in an HDL text-based environment would only require a few lines of code.

Conclusion

The intent of using Logisim-Evolution with the Basys 3 FPGA in the DE course is to provide students from two unique majors with an introduction to the essential concepts, tools, and workflow of digital logic design without a prerequisite of HDL programming knowledge. which it appears to do well so far. However, it is likely not ideal for certain advanced applications. Early observations based on student feedback and increased productivity suggest that students are more interested and engaged in the material since introducing Logisim-Evolution and Basys 3. By increasing the number of real-world projects into the course, students have indicated that they can make more connections to their other coursework and future career goals. The ability to translate designs from the most basic gate symbols (which can begin with truth tables or mathematical expressions) to the code needed to run on an FPGA has given students the ability to see how everything fits together.

Based on the lessons learned in Fall 2021, the instructor continued using Logisim-Evolution and Basys 3 in Spring 2022. The first lessons involved circuit basics and AOI logic gates. Students again responded well to interface and user experience. The instructor plans to introduce Verilog and VHDL coding later in the course after increasing confidence in CAD-based design and circuit fundamentals. This will ideally allow students to see a greater relationship between the schematic and text-based approach. Finally, the instructor is considering increasing rigor of course material and projects, as more topics can be covered in less time. Logisim-Evolution software provides novice users with an intuitive interface and requires less troubleshooting than the Vivado Design Suite. Additionally, the ability to utilize the software on almost any system, coupled with the ability to use a variety of FPGA devices may allow new opportunities for flexible learning modalities, which has been a critical issue for hands-on learning, especially during the time of the Covid-19 pandemic, where there is a greater reliance on personalized learning.

Plans for Future Study

Future work on this topic will include quantitative analysis on learning outcomes to examine how the changes to the course have impacted learning. Additional quantitative and qualitative studies can be conducted to examine issues such as perceptions of self-efficacy, attitudes, and relevance to career goals. A comprehensive review of other institutions' DE programs and approaches may also be valuable in assessing the practicality and potential effectiveness of this course structure and teaching pedagogy. Finally, a goal of the authors is to better understand implications of this course structure as it may be useful in other settings, such as with K-12 and/or informal STEM practitioners, where introductory concepts of digital logic and electronics are often explored in an applied, hands-on manner.

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