AC 2007-2039: PROJECT-BASED LEARNING FOR A DIGITAL CIRCUITS DESIGN SEQUENCE AT HBCUS

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Abstract

In today's globally competitive business environment, technology-based companies are looking for and expect to hire workers who have the skills necessary to successfully perform in a changing knowledge-based society. Minority students of today enter an increasingly globalized world in which technology plays a vital role. They must be good communicators, as well as great collaborators. The new work environment requires responsibility and self-management, as well as interpersonal and project-management skills that demand teamwork and leadership. It is essential that academic institutions equip future graduates with the essential skills to be an integral part of this change. In traditional classrooms, students typically work on simple assignments that emphasize short-term content memorization. They work individually and rarely have the opportunity to make presentations. Project-based learning (PBL) is designed to put students into a students-as-workers setting where they learn collaboration, critical thinking, written and oral communication, and the values of work ethic. PBL applied to Digital Circuits and Design Sequence (DCDS) courses addresses the need to provide undergraduate electrical and computer engineering students with such capabilities as they relate to real-world applications. This strategy addresses the goal of improving the quality of undergraduate Science, Technology, Engineering, and Math education through new learning techniques and teaching strategies. The *goal* of the DCDS is to improve student learning of theoretical concepts in digital circuitry through project-based learning exercises using a field programmable gate array (FPGA) platform for rapid prototyping of complex designs. FPGA-based platforms offer real-time prototyping of complex digital designs, allowing system verification and optimization in an environment that resembles the target system. DCDS relates and connects student learning in laboratory sessions that traditionally involve isolated and stand-alone activities. This paper focuses on the introduction of PBL using rapid prototyping to an introductory course in Logic Circuits. The rapid prototyping design sequence will be applied to several undergraduate engineering courses with the intent to help prepare students for industry or research through application-driven exercises. DCDS *objectives* are to (1) Create laboratory exercises for hands-on experience to enhance students' conceptual learning; (2) Link theory-based learning to real-life applications; (3) Increase retention of technical material for future courses; (4) Improve laboratory skills of students; and (5) Improve student confidence and attitude about their future profession. The development of an improved course sequence to successfully engage students in designing digital circuits and applying this knowledge to the real world has the potential to impact other such courses elsewhere. Project-based learning in a DCDS will benefit populations underrepresented in the field of engineering. Also, several academic institutions, including community colleges and K-12 schools have been identified as institutions that could benefit from the activities of DCDS.

1 Introduction

1.1 Historical Background

Some Historically Black Colleges and Universities (HBCU) are state-assisted institutions by legislative designation, serving a diverse ethnic and socioeconomic population and a land-grant institution by federal statute. HBCU's are committed to preparing undergraduates in a range of careers including but not limited to engineering, computer science, natural sciences, architecture, business, technology, criminal justice, and the humanities, education, agricultural sciences, nursing, mathematics, and the social sciences. Also some HBCU's are committed to advanced education through the master's and doctoral degrees in engineering and natural sciences. However, there are only a few offer computer engineering degrees at HBCU's, and all but one are accredited.

In most HBCU engineering programs the majority of the students are Electrical and Computer Engineers. For example, the total enrollment of Prairie View A&M University College of Engineering Graduate and Undergraduate Program currently is 860. The enrollment for Electrical and Computer Engineering is 277 which is 32% of the overall population. The enrollment for Computer and Electrical Engineering Technology is 189 which is 22% of the overall population. The impact of the work done in this exploratory investigation would be able to affect up to 54% of the entire College of Engineering.

Furthermore, as reported in [1[1]], 15 years ago, HBCUs represented greater than 30% of the underrepresented groups going into an industry, and today still contribute to 28% of the minority students entering into the computer science areas. In total, there are over 300 engineering schools in the country and HBCUs represent a subset of about ten. For one out of 30 schools, HBCUs contribute to 25 to 30% of minorities in industry. This is a major impact when examining the total picture.

1.2 Motivation

The growth and proliferation of new high-tech digital systems, and the need for engineers who are able to design, interpret, and analyze them is the very core of our modern day engineering oriented society. Modern electrical and electronic products have an unobtrusive blending of state-of-the-art communications technology, computer hardware, computer networking, and sophisticated application software, with design algorithms based on intelligent control incorporating fuzzy logic, neural network and a variety of new design oriented tools to produce consumer and commercial devices. The Internet and new design tools are making the understanding, usage and marketing of these new devices more convenient, and more economical. With companies using the Internet to perform operations more efficiently, and with a wide array of products to sell, there is a need for engineers with a background that include and understanding of logic devices and the and the incorporation of those devices into a functional digital system.

HBCUs have recognized the background requirements for the modern engineer to be able to design digital systems and apply them to real world situations. The demand for the need of engineering with a digital background is so demanding that new courses have been added to the curriculum and existing courses have been upgraded. Name of departments have been changed from Electrical Engineering to Electrical and Computing Engineering.

As a requirement for electrical and computer engineering students they must complete required mathematics, physics and C programming courses, as well as required humanities and social science courses. After completing basic courses the student will take the basic course of network theory. Throughout the network theory course, the student will be introduced to various software analysis packages and will solve circuit problems using Pspice, Matlab and Multisim. After completion of Network Theory I the student is ready to take their first digital course.

An important element of a digital design laboratory is to implement or build the device to test the design. Two approaches have generally been used. One is the traditional, graphical method using logic symbols and connections to describe the design and construction for hand wiring of devices. A more recent approach common to industry uses the computer as a tool to develop and test a description of the design given in a hardware language program of the circuit. The design can then be simulated on the computer and, when verified, can then be stored into a large, general circuit. Both methods are relevant but, because of the time required to hand design and construct circuits in the traditional way and the lack of scalability, computer aided methods are used almost exclusively.

At some schools, MultiSim has been a stand-alone tool for analog and digital design. As MultiSim serves both areas, a software tool is needed to integrate field-programmable gate array boards into digital design curricula for rapid prototyping. Xilinx and Altera have been major providers of software and hardware for university campuses. For example, Xilinx has a University program where professors and students have access to software tools and hardware development boards for undergraduate, graduate teaching, or research. They have a community of over 1,800 universities across the world using their systems in teaching and research and sharing course information. Xilinx software and hardware will serve as the platform for redesigning of new curricula of courses.

FPGA-based platforms offer real-time prototyping of complex digital designs, which allows system verification and optimization in an environment that resembles the target system. Implementing a design as an FPGA-based prototype has three applications. The designer can use high level hardware description for real-time verification of a circuit in a single large FPGA. Second, the designer can verify multiple circuits within an FPGA implementation. Third, by providing a platform for hardware/software co-verification, prototyping provides flexibility to verify software and hardware functionality in tandem at or near real-time speeds early in the design flow.

2 Scope and General Goals

2.1 Project Goals

In today's competitive society, it is important to pursue the kinds of innovative, technology-driven curricula essential to preparing students for life in the changing knowledge-based economy. It is essential that academic institutions equip future graduates with the skills necessary to be an integral part of this change. Companies are searching to add tech-savvy workers to their environment. Today's students learn at a faster rate when the classroom education is combined with the fast evaluation in a technological environment. Engaging laboratory assignments, combining theory with real-world problems, and teaching large number of students from diverse backgrounds are challenges faced in undergraduate education.

This paper presents a small, exploratory investigation for a solution to create this academic environment to educate our students. DCDS addresses the need to provide undergraduate electrical and engineering technology students with such capabilities as they relate to real-world applications. The DCDS project's *goal* is to improve student learning of theoretical concepts in digital circuitry through project-based learning exercises using a field programmable gate array (FPGA) platform for rapid prototyping of complex designs.

Project or problem-based learning is an instructional method that challenges students to think critically and enhance their ability to analyze and solve real world problems, develop skill in gathering and evaluating information needed for solving problems, gain experience working cooperatively in teams and small groups, and acquire versatile and effective communication skills. In using FPGAs, students will be able to significantly reduce the time required to develop products for the computer, peripheral, telecommunication, networking, industrial control, instrumentation, high-reliability/military, low power portable, and consumer markets. FPGAs supplies more than half of the worlds demands. Problem-based digital design projects will be created to and integrated in various undergraduate courses (*e.g.*, logic circuits, digital design, microprocessor systems design, computer architecture and advanced logic design) which span two departments. Methodologies involving design, construction, testing, and structured programming techniques are emphasized during the courses. The investigator believes that the skills learned by implementing problem-based projects on rapid-prototyping systems are desired by today's employer.

The proposed curricula project goal stems from two academic perspectives. The first perspective is developing a FPGA based rapid prototyping digital design laboratory, where students will learn how to program and carry out the design process using a very high-level hardware description language. The second perspective is to use the idea of project-based learning to enhance student learning and retention of material taught in the lecture course. Together, these perspectives will be able to help achieve the DCDS *objectives* which are to (1) Create laboratory exercises for hands-on experience to enhance students' conceptual learning; (2) Link theory-based learning to real-life applications; (3) Increase retention of technical material for future courses; (4) Improve laboratory skills of students; and (5) Improve student confidence and attitude about their future profession. These two perspectives and how they relate to the objectives are explained in the following sections.

2.2 Rapid Prototyping using FPGAs

Wilson, et al., in http://www.cudenver.edu/~bwilson/training.html defines Rapid Prototyping as in a design process where early development of a small-scale prototype is used to test out certain key features of the design [2]. Traditionally, students have designed logic circuits in a linear fashion based on defined needs goals. These steps are shown in Table 1. Increased development time, costly mistakes, and less communication, has been a result when designing more complex and challenging systems [3]. In Whitten, Bentley, and Barlow, system designers at very early stages of planning of large-scale systems, a small-prototype is built to exhibit key features of the intended system [4]. The prototype is explored and tested in an effort to get a better understanding on the requirements of the larger system. The overall benefit is that it allows for the designer to tryout key concepts at early stages of the design cycle when the costs are small and changes can be more easily made.

The procedure, in which standard digital circuits are designed, is listed in Table 1 for both traditional and current methods. Note that generally, the analysis and design methods are the same. The primary difference being in how the design is constructed (beginning at Step 5), whether wired from discrete devices or programmed into a single, general device.

Table 1: Standard digital design steps for logic circuits.

1. Informal statement of problem. 2. Formal statement in form of truth table of circuit inputs and outputs. 3. Extract Boolean expression from truth table. 4. Simplify expression using algebraic or mechanical methods (e.g. Karnaugh maps).	
Traditional	**Current**
5. Realize simplified expression in corresponding logic gate representation. 6. Specify real physical devices for each logic gate function, appending pin connections. 7. Construct real circuit making pin connections between physical devices.	5. Specify hardware description language module for logic expression. 6. Simulate logic expression as operation of hardware circuit for verification. 7. Program general device with hardware description.

Prototyping can be relevant to all kinds of training development projects however it is most valuable in the design of computer-based systems [2]. For example in developing a customizable digital scoreboard strictly from identified needs and goals without any prototypes, using the traditional method, would be very challenging when constructing the real circuit making pin connections between physical devices. This kind of project could take weeks, if not months to complete for an introductory level digital circuits course.

In addition to rapid prototyping, hardware can be modeled in many different ways, i.e., transistor or junction, gate, or at a higher level using hardware description language (HDL) such as VHDL or Verilog. HDLs can describe the circuit's operation, its design, and tests to verify its operation by means of simulation. VHDL which stands for Very High Speed Integrated Circuits (VHISC) Hardware Description Language and Verilog are the standard HDL's that exist today. VHDL was developed and adopted as a standard by the Institute of Electrical and Electronic Engineers (IEEE) in the US in 1987[5]. Verilog was adopted in 1995. Both have been used in industry, and currently Verilog is the de facto standard [6]. The advantages of using HDLs for modeling digital circuits are:

- behavioral models easy to create and verify
- fast logic level simulation
- makes possible simulation of large and very large circuits
- accurate timing description using hold, setup, and minimum separation times
- models can be simulated using many standard semiconductor logic simulators
- models easy to transfer between computer systems

By implementing rapid prototyping in the laboratory courses, DCDS will be able to carry out the following objectives, create laboratory exercises for hands-on experience to enhance students' conceptual learning and increase retention of technical material for future courses.

2.3 Project-Based Learning

Project or problem-based learning (PBL) is an instructional method. As defined by Dr. Howard Barrows and Ann Kelson of Southern Illinois University School of Medicine, PBL is a curriculum and a process that consists of carefully selected and designed problems that demands from the student acquisition of critical knowledge, problem solving proficiency, self-directed learning strategies, and team participation skills [[7]]. All of which are needed skills in industry. The process copies the systemic approach to resolving problems or meeting challenges that are encountered in life and career. PBL began at McMaster University Medical School over 25 years ago, and has been implemented in schools around the world, K-12, undergraduate and graduate.

PBL is a model for classroom activity that shifts away from the classroom practices of short, isolated, teacher-centered lessons and instead emphasizes activities that are long-term and integrated with real world issues and practices. One of the benefits of applying project-based learning is the way that it motivates students by engaging them in their own learning. It provides opportunities for them to pursue their own interests and questions and make decisions about how they will find answers and solve problems. The traditional teacher and student roles change, where the student assumes increasing responsibility for their learning setting a pattern to become successful life-long learners, and the teacher becomes a resource, tutor, and evaluator, guiding them in their problem solving efforts. Another benefit is that is helps make learning relevant and useful to students by establishing connections to life outside the classroom, addressing real world concerns, and developing real world skills. The skills learned are desired by today's employer, such as the ability to work well with others, make thoughtful decisions, take initiative, and solve complex problems. DCDS will focus on introducing several projects that involve the application of theoretical exercises to real-life problems. Within each project, students will have the opportunity to work on pieces that come together to answer a real-world problems. The time frame designed for each project is two to three weeks.

2.4 Project-Based Learning

A new model for the engineering module content delivery in DCDS was introduced in Table 1. The adopted DCDS model blends the three elements of the Triangulated Learning Model; (1) simulation, (2) construction, (3) connection, the four elements of the Kolb Learning Cycle; (1) concrete experience, (2) reflective observation, (3) abstract conceptualization, and (4) active experimentation often used in engineering, with the 5E Learning Cycle; (1) engagement, (2) exploration, (3)explanation, (4) extension, and (5) evaluation, which are often used in science education. Table 2 shows the alignment of the DCDS rapid-prototyping model with TLM, Kolb, 5E Learning cycles with Science as Inquiry from the National Science Education Standards.

Table 2. Module descriptions and standards map.

Proposed DCDS Rapid-Prototyping Cycle	***TLM Elements***	***Kolb Learning Cycle***	***5E Learning Cycle***	***National Science Inquiry Standards***
Informal statement of problem	Simulation	Concrete experiences	Engage	Learner collects certain data
Formal statement in the form of truth table of circuit inputs and outputs Extract Boolean expression from truth table Simplify expression using algebraic or mechanical methods (e.g., Karnaugh maps)		Reflective observation	Explore	Learner formulates explanation after summarizing evidence
Specify hardware description language module for logic expression	Construction	Abstract conceptualization	Explanation	Learner poses a question
Simulate logic expression as operation of hardware circuit for verification		Active experimentation	Extend	Learner determines what constitutes evidence and collects it
		Concrete experience	Evaluate	Learner formulates explanation after summarizing evidence
		Reflective observation		Experimental design Hypothesis testing Conducting the experiment Reformulating explanation after summarizing both evidence and feedback
Program general device with hardware description	Connection	Reflective observation	Explanation	Learner communicates & justifies explanation based on data
		Abstract conceptualization	Extend	
			Evaluate	

2.5 Project Example

In the example taken from the University of Michigan, Introduction to Digital Design Course, Robbie and Renee the Robot were used as lab experiments. This example can be tailored to a real-world problem, such as an autonomous wheel-chair or automobile.

Robbie is the simpler robot which is attempting to drive to the beacon and stop. Robbie has three sensors and two independently controlled wheels. The sensors are mounted on the front, front-right and front-left of the robot, as seen in Figure 1. These sensors detect if the beacon is in a certain area (the cones indicated in Figure 1). If the sensor does detect the beacon it outputs a "1", otherwise it will output a "0".

The two wheels are driven independently. If a "1" is sent to the wheel it turns forward, but if a "0" is sent to the wheel it doesn't turn. Robbie will go straight if both wheels are turning forward, and will stop if both wheels are stopped. In addition, Robbie turns right if the left wheel is going forward while the right wheel isn't turning, and would turn left in the symmetric case (the left wheel stooped and the right wheel going forward).

Robbie should follow the following rules:

- He is to go straight if the forward sensor detects the beacon and/or both the left and the right sensors detect the beacon.
- Otherwise, if either the right or the left sensor detects the beacon, he is to go in that direction.

Otherwise, he is to stop.

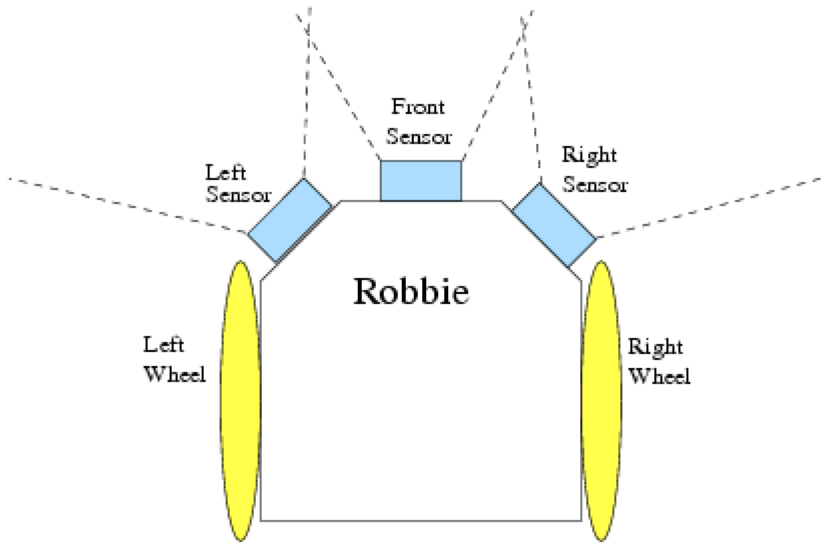

Figure 1: Robbie the robot, with sensors and wheels.

Renee is similar to Robbie, but there are some significant differences. First, she has only two beacon sensors (left and right), but those sensors provide information about distance. Secondly, she has bumper sensors (which tell her if she has hit something). Lastly, her wheels can go in reverse in addition to going forward. These changes are detailed below:

1. **Beacon sensors:**
   Renee uses two more sophisticated sensors in place of Robbie's three sensors. The one on the front is removed. The sensors provide information about how strong of a signal they are getting from the beacon. The sensors return a 3-bit unsigned number. The closer the beacon (and more toward the center of the cone of a given sensor) the higher the value they return.
2. **Bumper sensors:**
   Renee has four of these, one on the front, left, right and back. They return a "0" if Renee has bumped into something in that direction, and a "1" if she has not.

3. **Wheels:**
Renee's wheels can go forward and backwards as well as stopping. She can now do the following actions:

Action	Left Wheel	Right Wheel
Forward	F	F
Left	S	F
Right	F	S
Stop	S	S
Hard Left	R	F
Hard Right	F	R
Left Back	S	R
Right Back	R	S
Reverse	R	R

Table 1: How Renee uses her wheels to perform her actions.

Renee's interactions with the world

Renee should head in the direction of the sensor which indicates it has the strongest signal. If both signals are zero Renee should stop. If the two signals are the same, Renee should go forward. However, the beacon sensors are ignored if Renee has hit something: in that case her first priority is to move away from the thing she hit. If any of her bumpers detect a collision, she should follow these rules:

- If her front bumper sensor is the only one detecting a collision she should move in reverse.
- If her back bumper sensor is the only one detecting a collision she should move forward.
- If her left bumper sensor is the only one detecting a collision she should move right back.
- If her left and front bumper sensors are detecting a collision she should move right back.
- If her right bumper sensor is the only one detecting a collision she should move left back.
- If her right and front bumper sensors are detecting a collision she should move left back.
- If her left and back bumper sensors are detecting a collision, she should move right.
- If her right and back bumper sensors are detecting a collision, she should move left.

If any two bumper sensors on opposite sides are detecting a collision (front and back or left and right) she should stop.

3 Evaluation of Objectives

The DCDS project's *goal* is to improve student learning of theoretical concepts in digital circuitry through project-based learning exercises using a field programmable gate array (FPGA) platform for rapid prototyping of complex designs. The *objectives* of DCDS are to (1) Create laboratory exercises for hands-on experience to enhance students' conceptual learning; (2) Link theory-based learning to real-life applications; (3) Increase retention of technical material for future courses; (4) Improve laboratory skills of students; and (5) Improve student confidence and attitude about their future profession.

In constructing any evaluation for the perspective students it is important to keep the following three principles; 1) Students must learn from the procedure; 2) The procedure must be consistent with the goals of the program; 3) Students must be given an opportunity to display not only their weaknesses but also their strengths. The project must be evaluated both on the process and content. The TRIPSE (tri-partite problem solving exercise) process will be used to evaluate the content of each problem-solving exercise and the individual performance of the students [[8]]. TRIPSE was developed by P. K. Rangachari for an undergraduate course in introductory pharmacology given at McMaster University. The activity is divided into three stages, where the fist stage (problem definition), students will be given a design problem with a minimal amount of information. The students will then use that information to gather a plan to identify the items of information needed to solve the problem. In stage two, they will then conduct an information search and choose one of their explanations and design a suitable test or tests to confirm or deny their expectations. In stage three, re-assessment will be done, given more information (a set of references) to check their original explanations/tests in view of the new information. Also noted is that there is really no one correct answer, only sets of answers ranging in credibility. Each phase is evaluated separately, and an outline describing the essential factors that needed to be explained, as individual written comments are to be given. Some of the issues to be considered when conducting this process are class size, faculty and library resources, and the level of the students when they take the courses. In order to address this problem, with funding from this investigation, two undergraduate students and a graduate student will be supported to assist in the investigation.

In the end of the term, a questionnaire will be given to the students to indicate on a 5-point scale (1 = low to 5 = high) the strength of their agreement with the following statement defining the expectations of the teacher:

"Students will use a novel problem to frame hypotheses (explanations), devise experimental tests, and re-assess their answers in light of new information. This exercise was designed to simulate the scientific process in practice."

Students would then be asked to grade the exercise on a standard University scale (D = poor to A = outstanding). These questionnaires will be given over a period of two years and the information gathered will be used for continual process improvement.

4 Summary

The proposed curriculum project is designed to maximize outreach and mentoring opportunities via lecturing engagements at non-Ph.D.-granting electrical engineering departments, including other Historically Black Colleges and Universities and community colleges in the nearby area. Currently, the investigators are active coordinators in their respective departments and serve as advisors and mentors in STEM programs that seek to recruit, retain, and mentor minority students.

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