Improving Student Understanding of Digital Systems Design with VHDL via Inductive Instruction

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Abstract

This paper introduces inductive instruction strategy that is applied to Digital Systems design with VHDL class. This class demands extensive simulations using Xilinx ISE design suite and FPGA board for implementation and testing, which is tough and challenging for first-time learners. To improve students' learning experience and outcomes, we integrate inductive instruction, active learning techniques and demonstration-based learning in the Digital System design class. In this paper, a specific circuit, e.g., 7-segment LED time-multiplexing circuit of S3 board, serves as an example to illustrate inductive instruction. The traditional instructional methods are adopted in 2014 while inductive instruction strategy is applied in 2015 for the first time and is further enriched in 2016. Students' learning outcomes are recorded from 2014 to 2016. We observe that students have better understanding on the topics in 2015 and 2016. In addition, the teaching evaluations have improved over the past three years.

I. Introduction

As educators, we strongly agree that the primary mission of education is to prepare students for future leadership roles of the profession as well as to develop their abilities to remain competency through a lifelong learning experience. Effective teaching and active learning is the most important element to accomplish the above goals. The aim of teaching is not only to deliver knowledge to students, but also to transform students from passive recipients into active learners who are capable of constructing their own knowledge [1].

Two primary challenges were identified in teaching engineering courses. Firstly, most engineering courses are traditionally taught deductively, that is the instructor introduces relevant theory to the students, demonstrates mathematical equations, and finishes the lecture using the solutions to two or more well-defined problems. Without connecting the course content to real-world applications, students' motivation to learn the topics is limited to course grades [4]. Engaging students for a 50-minute lecture has been another challenge for most educators besides improving students' motivation for learning. Some studies concluded that although majority students can pay high attention to the lecture when it begins, the attention level declines dramatically after 10 to 15 minutes [6]. Instructors have tried to implement various instructional methods to maintain students' interest in the topic(s) beyond the 15 minutes.

Inductive teaching and active learning have been acknowledged as efficient instructional strategies that increase undergraduate student performance as well as their interests in science, technology, engineering, and mathematics (STEM) disciplines [7]. Inductive teaching uses experiments, case studies, and real-word problems as challenges to stimulate students' interests in the course material and encourage the students to approach to higher level of learning domain [5]. Active learning is defined as instructional methods that engage students in the learning process through interactive learning activities in class [8]. Hake [9] compared the results of conceptual understanding and problem solving tests from 4458 students in introductory physics courses using active learning method and those of 2084 students in traditional courses. The results showed statistically higher average gains in the classes using active learning methods. Inspired by inductive teaching and active learning approaches, some textbooks started to introduce fundamental topics by using cases/projects instead of focusing on the calculations in STEM disciplines [12].

Through our teaching experiences, we have also observed that students learn more effectively when videos and in-class demonstrations are introduced as supplements to lecture notes, especially when software and hardware are used. For example, CENG342 Digital Systems is a required course for Computer Engineering (CENG) students at South Dakota School of Mines and Technology. This course is expected to present the basic concepts and mathematical tools that are applicable to the analysis and design of digital systems. The VHDL hardware description language is introduced and used intensively as a design tool. A variety of VHDL implementations including combinational circuits, sequential circuits, arithmetic circuits and state machines are studied.

The course of Digital System design with VHDL demands intensive VHDL coding practice, extensive simulations using Xilinx ISE design suite and testing of circuitry using Xilinx FPGA Prototype Boards (i.e., Xilinx Spartan 3 board) [3]. It is a challenging course for first-time learners who have no hardware programming experience. In 2014, the traditional instructional methods that are primarily based on lectures were adopted. The traditional instructional methods are not effective to clarify students' confusions about the principles covered in the course. We have incorporated inductive instruction, active learning techniques and demonstration-based learning to improve students' learning performance in digital systems design with VHDL since 2015. Specifically, a variety of learning technologies, including video, hands-on demonstrations and other new aids are introduced into this class. In 2016, we further enriched inductive instruction for more circuit designs. In this paper, we will use a specific circuit, e.g., 7-segment LED time-multiplexing circuit of S3 board, as an example to illustrate inductive instruction implemented in our class.

Longitudinal data on students' performance in this class have been collected from 2014 to 2016. Assessed by laboratory reports, midterm and final exams, the students had better understanding on the topics than those in the previous semesters. The teaching evaluations from students continually improved over the past three years. We have received more positive comments from students with regard to this course as well.

The rest of the paper is organized as follows. Section II presents inductive instruction using 7-segment LED time-multiplexing circuit as an example. Section III discusses student attitudes in the engineering course through active learning and hands-on activities. Section IV draws conclusions.

II. Inductive Instruction Design

In this section, we will illustrate how to apply inductive instruction teaching strategy into CENG342 through 7-segment LED time-multiplexing circuit of FPGA board as an example. This course demands extensive uses of FPGA board for implementation and testing. Xilinx Spartan 3 is the FPGA board we adopt. There are four 7-segment LED displays on the Spartan 3 board and we use them very frequently to display output during testing. Therefore, it is critical to fully understand how the 7-segment LED displays work. All four LEDs share the same control signals to light up 7 segments. S3 board uses a time-multiplexing sharing scheme for four 7-segment displays. Four displays have individual enable signal but share the same control signals to light the segments. It can be seen that this configuration can enable only 1 display at one time. The enable signal is designed as active-low, which means “0” will light up the display while “1” makes it blank. Fig. 1 shows an example when the enable signal an=“1110”, which lights the rightmost 7-segment LED display.

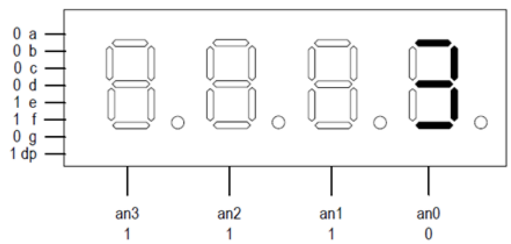
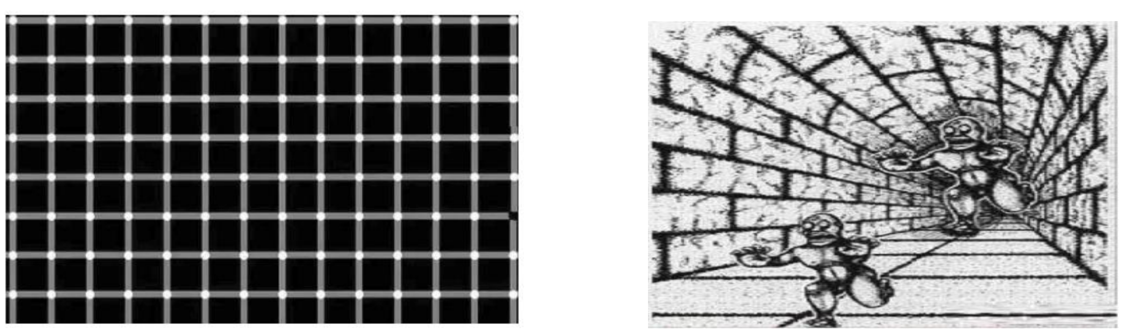


Fig. 1 Time-multiplexed 7-segment display illustration: the rightmost display is on when enable signal is “1110” [3].

The four 7-segment LED is widely used in most of our examples and lab assignments to display different digits (e.g., 0-9, a-f) on the S3 board. Many students fail to understand how S3 board is able to display four different digits on four 7-segment LEDs because they all share the same control signals. Inductive instruction, particularly active learning techniques and demonstration-based learning, are employed to improve student’s learning. Specifically, we enrich the lectures about LED time-multiplexing circuit of S3 board with images to first illustrate how human being eyes are often tricked and then followed by hardware demonstrations. To demonstrate the illusion of our eyes, Fig. 2 (a) (b) are borrowed online to test students’ eyes [10, 11]. Students are asked the intersection dots are white or black in Fig. 1 (a). It seems like we saw some black dots, but actually they are all white. Another example we introduce in class is Fig. 1 (b). Students are excited to guess which monster looks bigger. The majority answer is that the back (or top) one looks bigger. In fact, both are in the same size!



(a) (b)

Fig. 2 Examples of human’s eyes are often tricked [10, 11].

Similarly, if the refreshing rate of 7-segment display is fast enough (e.g., 1000Hz), the human eyes cannot distinguish the on and off intervals of the LEDs. As a result, it seems like all 4 LEDs light up simultaneously, but they are actually lit in turn.

Afterwards, students are engaged in discussions guided by a series of questions, such as (1) the proper refreshing rate is around 1000Hz. However, S3 board has a build-in 50MHz clock. How to ensure LEDs take turns with an approximate 1000 HZ? and (2) Binary counter is a good tool to achieve this goal. How many bit binary counter is needed? Finally, after completing designing the LED time-multiplexing circuit, we use Xilinx S3 board to demonstrate different consequences with or without the LED time-multiplexing circuit, with different refresh rates, etc. Some demonstrations are depicted in Fig. 3.

Fig. 3 (a) Without time-multiplexing module, all 4 LED displays always show the same digit (e.g., F); (b) With time-multiplexing module, the rightmost LED display is enabled only to show F; (c) With time-multiplexing module, 4 LED displays show a different digit on each.

The inductive teaching strategy is applied to teaching other topics in this class as well. We also make efforts to connect class content to real-world applications. For example, we assign several labs related to real-world applications including stopwatch design and vending machine design to motivate students' interests. The last project is to design a simplified MIPS digital processor to implement a small subset of its instruction set. The slide switches on S3 board are used to load the 32-bit instruction, eight bits at a time. Once loaded, students will then execute that instruction. After execution, the slide switches on S3 board is used to select what information (e.g., value of operands or results) to be displayed on the 7-segment LEDs. This project combines hardware architecture, instruction sets, and software languages. It is a comprehensive and complex one, which take the students to reach a remarkably higher level of digital system design.

III. Teaching Result Evaluation

In this section, we will assess students' learning performance in CENG342 during 2014-2016. CENG342 is a 4-credit course, which consists of 3-credit lectures and 1-credit laboratory work. We meet three times a week for the lectures and each lasts 50 minutes. On average, there is a lab assignment every other week excluding exam weeks. The student enrolment is 16, 20 and 20 from 2014 to 2016. The same learning outcome form is used in all three years (2014-2016) and longitudinal data have been collected. The student learning outcome form is designed to cover the fundamental materials taught in the class. Table 1 summarizes several selected outcomes. Each outcome is tested by carefully designed homework/lab assignment and exams. For instance, Outcome1 (i.e., fully understand combinational circuits and how to implement them with VHDL) is evaluated by 4-bit greater than circuit design, Octal-to-Binary Encoder design, etc. in homework assignment, BCD (binary-coded-decimal) Incrementor design and testing using S3 board in lab assignment, and simple ALU (Arithmetic Logic Unit) design in Exam 1.

As mentioned previously, the traditional instructional methods were adopted in 2014. We first introduced inductive instruction into class in 2015 and further enriched in 2016. The students' learning performance for all outcomes (0-4 scale) is evaluated based on students' self-assessment, homework/lab assignment and exams. Fig. 4 compares the student learning outcome during 2014-2016. It can be seen that students had better understanding on the most of topics than those in the previous semesters.

Table 1 Selected Student Learning Outcome Description during 2014-2016

Outcome	**Student Learning Outcome Description**
1	Fully understand combinational circuits and how to implement them with VHDL.
2	Fully understand sequential circuits and how to implement them with VHDL.
3	Understand how to design and implement any state machine manually.
4	Understand how various arithmetic circuits work and how to design and implement them with VHDL.
5	Understand how to link various digital building blocks to create a larger hierarchical design.
6	Understand at a system level how a digital processor works and how to design and implement a processor with VHDL
7	Understand the link between hardware architecture, instruction sets, and software languages.

In addition, students' engagement is improved after adopting inductive instruction. More students participate in class discussion. The teaching evaluations have improved since 2014 (from 4.1 out of 5 to 4.7). The instructor receives more positive comments from students with regard to this course as well. Students comment that the materials of this class are clearly and well delivered; they have enjoyed the class and look forward to taking the instructor's classes again. Some students' comments in 2016 are copied as follows.
"I enjoyed the hands-on part of this course and the practicality of the labs (2016)"
"I was very impressed with how well this class went. The homework and labs were very appropriate with respect to the lectures. (2016)"
"I really enjoyed this class. I felt like it was well structured, presented in an easy to understand way, and contained a lot of demonstrations. Overall, this class was excellent. (2016)"

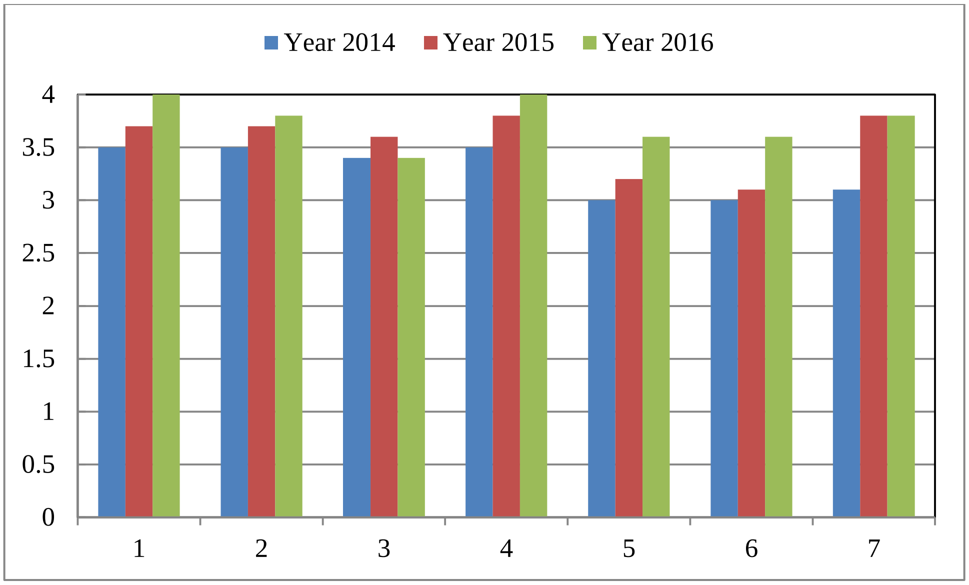


Fig. 4 Students' learning outcome in 2014-2016 with 0-4 scale.

IV. Conclusions

We have integrated inductive instruction particularly demonstrations and active learning approaches in the Digital System design class. This paper selects a fundamental circuit, e.g., 7-segment LED time-multiplexing circuit of S3 board, as an example to demonstrate how we teach class using inductive instruction. Students' learning outcomes and engagement are improved after adopting inductive instruction strategy in class. Consequently, students have gained knowledge better on the topics. The teaching evaluations also improved from student's feedbacks. It verifies the effectiveness of active learning approach. In the future, we will continually improve our teaching by enriching active learning methods and seeking other novel learning strategies.

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