The BitBoard - Bridging the Gap from Gates to Gate Arrays

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Carroll has co-authored two textbooks, a tutorial book, and numerous papers and technical reports. He has received an American Society for Engineering Education Outstanding Young Faculty Award, two National Aeronautics and Space Administration Technology Innovation Awards, and three IEEE Computer Society Service Awards. He is an IEEE Computer Society Golden Core Member and a recipient of the IEEE Third Millennium Medal.

Carroll served as Dean of the College of Engineering at UTA from January 1, 2000 to August 31, 2011. During his service as dean, the College of Engineering experienced an enrollment growth of more than fifty percent, an increase of research expenditures from under $10M per year to more than $40M per year, and a growth of the faculty of about sixty percent. Over the same period, capital projects totaling more than $180M were started and completed.

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Abstract

The BitBoard© is a low-cost device that can be used with the Altera DE1[1] Development and Education Board to support gate-level and field programmable gate array (FPGA) laboratory exercises in introductory digital logic courses. Details of the device and experiences using it in a sophomore-level course are given in the paper. Plans to use the device for homework and in-class active learning exercises are also explored. A take-home laboratory kit called The BitBox© which incorporates The BitBoard and a DE1 is also described. The paper discusses the results of a student survey on the usefulness and reliability of the device and the kit. Observations and results of the survey suggest that The BitBoard and The BitBox are effective educational tools for teaching digital logic fundamentals and have a range of application well beyond the local environment. The BitBoard and provides a seamless way to bridge the gap from basic gate-level experiments to advanced FPGA projects using an integrated take home laboratory kit.

Introduction

This paper describes an innovative, low cost device called The BitBoard that was developed as an expansion board for education boards such as the Altera DE1[1] or DE0-CV[2] to enable a wide range of digital logic experiments from basic logic gates and flip-flops to advanced field programmable gate arrays (FPGA). The BitBoard is described later in the paper. Laboratory experiments and experiences using the device in an introduction to digital logic course are also discussed.

The BitBoard is the core of The BitBox©, a low cost take-home lab kit that students use to perform a series of logic design experiments that culminates with the design and realization of a simple processor. A systematic assessment of student responses to the effectiveness of The BitBox and The BitBoard is given in the paper.

The BitBoard is typically used for five gate-level laboratory exercises and the DE1 board for five FPGA-based experiments each semester. The course also requires a term design project that must be realized on the DE1 but may be designed with schematic capture, Verilog, or a combination of the two.

The convenience and low cost of The BitBox also makes it ideal to support homework assignments as well as in-class active learning or flipped classroom exercises. Plans for using it for this purpose are also described.

The remainder of the paper is organized in to seven sections – background and motivation, The BitBoard, The BitBox, laboratory exercises using The BitBoard, hands-on exercises for homework and in-class assignments, observations and student feedback, and conclusions and future plans.

Background and Motivation

The BitBoard is being used at The University of Texas at Arlington in *CSE 2441 Introduction to Digital Logic* which is a four semester-credit-hour, sophomore-level course following a standard three-hour lecture and three-hour laboratory format each week. It is required for computer engineering majors and elective for computer science and software engineering majors. The course covers the fundamentals of combinational and sequential logic circuits and has a discrete mathematics course prerequisite and an electrical circuits course co-requisite. Students are first introduced to basic logic circuit analysis and design at the gate-level and then move on to field programmable gate array (FPGA) designs and implementations later in the course. Students use the Altera Quartus II[3] software for design capture (schematic and Verilog) and for logic simulation. More details on the course can be found in an earlier paper[4].

The philosophy behind the course is to first teach students the basics of logic circuit analysis and design using gates and flip-flops and then move to FPGAs and Verilog. My justification for this approach is that technologies and design methods will continue to change and that basic fundamentals will continue to stay the same. So teaching students the fundamentals is the best way to prepare them for a long career. On the other hand, introducing students to the latest technology is also important since that helps them get a job. So the course is a compromise between these two points of view. Admittedly, the approach is based on my experience and observations rather than the results of educational research. It is also noteworthy that gate-level designs are still sometimes needed in practice, so I believe it is still important and useful for students to learn both gate-level and FPGA-based design.

The long-term viability of this approach depends upon the continuing availability of low cost SSI and MSI digital integrated circuits. My experience is that the parts we use are still readily available and that prices are stable. If and when this should change, the alternatives would be to place more emphasis on simulations and/or FPGAs. Meanwhile, it may be advisable to stock up on enough parts to allow time for a transition should it be necessary.

Before The BitBoard, we were using IDL-800 Digital Lab instruments to support the gate-level experiments and the DE1 for the FPGA experiments. The IDL-800's had served us well for many years but were showing wear and tear. Replacement costs for the IDL-800's exceed $400 per unit. So finding a lower cost option was one motivation for developing The BitBoard which cost about $60 each for parts and assembly.

Another motivation was to develop a take-home lab kit enabling students to work on their experiments and projects at home and at their convenience. Previously, students were given an IDL-800 solderless breadboard to take home for wiring circuits prior to coming to lab. This was not as effective as hoped since students still had to come to lab to test their circuits, so most chose to do the wiring in lab as well.

Given that we were already using the DE1 boards to support FPGA-based experiments, it was natural to explore ways to use it for the gate-level experiments as well. An unsuccessful search for an appropriate expansion board on the market led to the development of The BitBoard.

The BitBoard

The BitBoard is an expansion board for an Altera DE1[1] Development and Education Board or similar device and can be used for designing, constructing, testing, and experimenting with small digital logic circuits. It consists of a solderless breadboard, three 40-pin connectors, and a printed circuit board (PCB). Corresponding pins of each connector are permanently interconnected by the PCB. Figure 1 shows The BitBoard layout and nomenclature. Connector *A* is a 40-pin header plug used to connect The BitBoard to other devices such as an Altera DE1. Connectors *B* and *C* are 40-pin header sockets used to connect signals to the solderless breadboard using jumper wires.

A BitBoard connected to a DE1 via a forty-conductor ribbon cable is shown in Figure 2. The DE1 provides power and input/output to The BitBoard. Altera has recently released a new device, the DE0-CV[2], that is also compatible with The BitBoard.

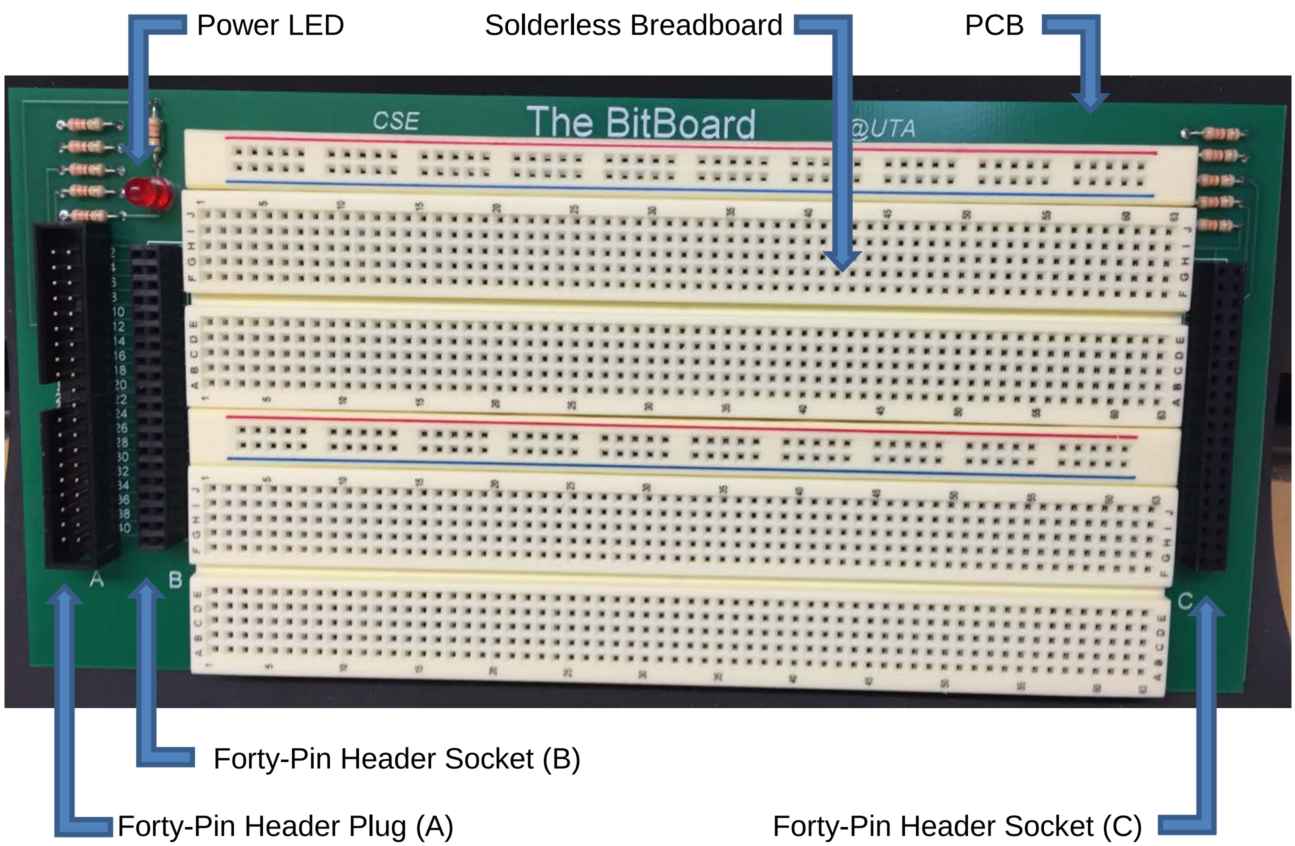


Figure 1 – The BitBoard© Layout and Nomenclature.

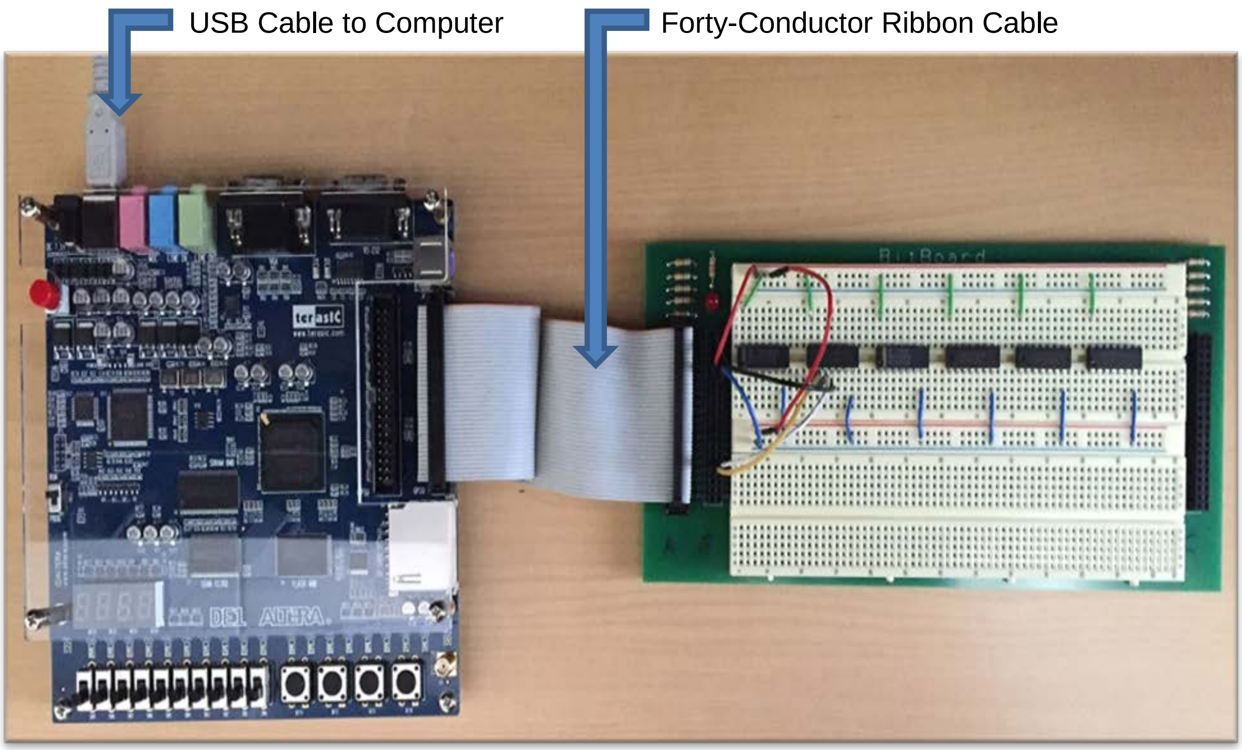


Figure 2 – DE1 Connected to The BitBoard©.

DE1 switches, LEDs, seven-segment displays, and power connected to The BitBoard are listed in Table 1. The mapping of these elements to The BitBoard header pins is shown in Figure 3.

Table 1 – DE1 Input/Output Devices Used on The BitBoard©

Device Type	***DE1 Names***	***BitBoard Pins***
Red LEDs	LEDR0 to LEDR9	1 to 10
Seven-segment Displays	HEX0 and HEX1	13 to 26
Slide Switches	SW0 to SW9	31 to 40
Push Button Switches	KEY0 and KEY1	27 and 28
Power	5 Volts	11
Power	3.3 Volts	29
Ground (2)		12 and 30

Interfacing The BitBoard to the DE1 requires the physical connections shown in Figure 3, and interface logic programmed in the DE1 Cyclone II FPGA. This logic, written in Verilog, links or maps the DE1 I/O devices to The BitBoard header pins as detailed in Figure 4. Note that some DE1 I/O devices are not accessible from The BitBoard due to pin limitations of the cable and connectors. Also note that the V5, V3.3, and GND pins are fixed in function and placement by the DE1 specifications while all of the remaining thirty-six pins are BitBoard specific in selection, placement, and organization. Interface logic for the DE0-CV is under development.

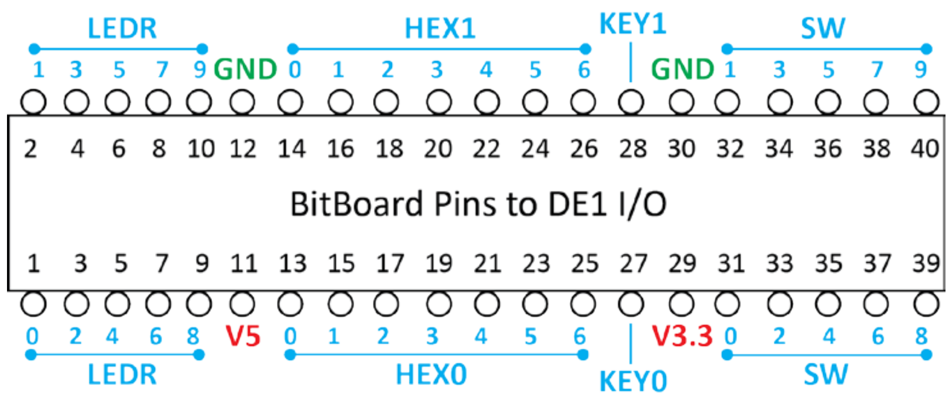


Figure 3 – Pin Mapping of The BitBoard to DE1.

The DE1 switches, LEDs, and seven-segment displays selected for mapping to The BitBoard were chosen specifically to support the needs of an introductory digital logic course. The placement and organization of these I/O pin-outs on The BitBoard headers was designed to facilitate wiring from the headers to the solderless breadboard and to most effectively utilize the available pins on the DE1 GPIO-1 header block.

The BitBox©

The BitBox© is a take-home lab kit consisting of a BitBoard, a DE1, an assortment of twenty-five integrated circuits, an assortment of jumper wires, and a carrying case as shown in Figure 4. Each student is assigned a BitBox for use throughout the semester. The BitBox costs came to less than $200 each.

Laboratory Exercises Using The BitBoard

To date, The BitBoard has been used to support the laboratory exercises in an introduction to digital logic course. Table 2 lists the exercises and identifies those performed on The BitBoard. In the future, it will also be used for homework assignments and in-class projects. These are described in the next section.

The laboratory exercises are structured as a sequence of design problems that culminates in the realization of a simple processor, called TRISC, for the course term project. Designs are hierarchically integrated so that one week's circuit becomes a component in a subsequent lab. For example the basic adders designed in Exercise 2 become a component for use in Exercise 3 which becomes a component used in Exercise 5. More detailed coverage of the hierarchical approach and TRISC can be found in a previous paper[4].

These exercises focus primarily on the design of arithmetic circuits and sequential circuits necessary for realizing the TRISC processor. Hence, students do not get hands-on experience with other fundamental concepts and applications such as circuit equivalence and finite state machines to name a few. Also, active learning and flipped classrooms have become popular as approaches for improving student learning through hands-on experiences. So using The

BitBoard for homework and in-class exercises to supplement the laboratory experiences and to support non-traditional delivery methods is explored in the next section.

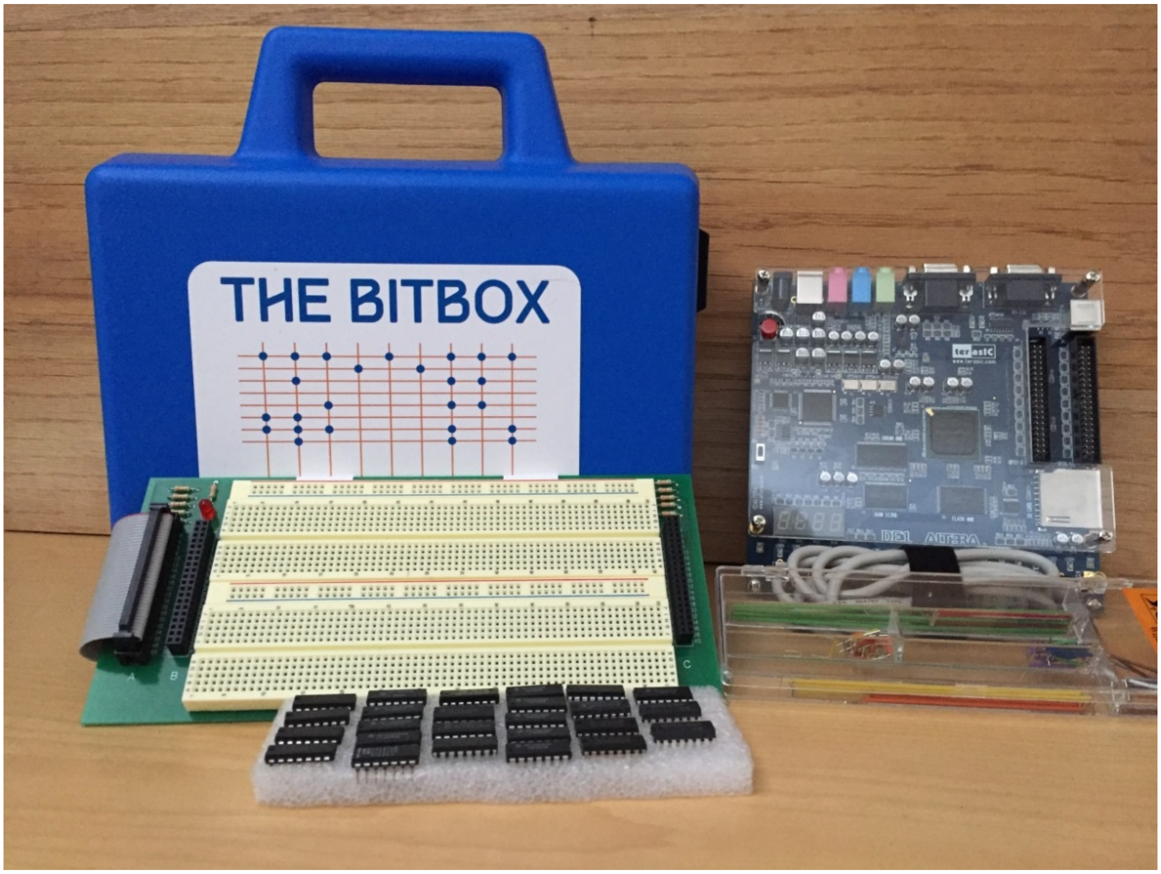


Figure 4 – The BitBox

Table 2 – Introduction to Digital Logic Laboratory Exercises

Exercise Number	*Topic*	*Implementation*
Exercise 0	Introduction to The BitBoard and Basic Gates	The BitBoard
Exercise 1	Introduction to Quartus II	Software
Exercise 2	Basic Adders and Subtractors	The BitBoard
Exercise 3	Two's Complement Adder/Subtractor	The BitBoard
Exercise 4	Programming the DE1	DE1 FPGA
Exercise 5	Four-Function ALU	DE1 FPGA
Exercise 6	Introduction to Synchronous Circuits	The BitBoard
Exercise 7	Counters and Displays	DE1 FPGA
Exercise 8	Finite State Machines	The BitBoard
Exercise 9	Processor Control Unit and RAM	DE1 FPGA
Term Project	TRISC Processor	DE1 FPGA

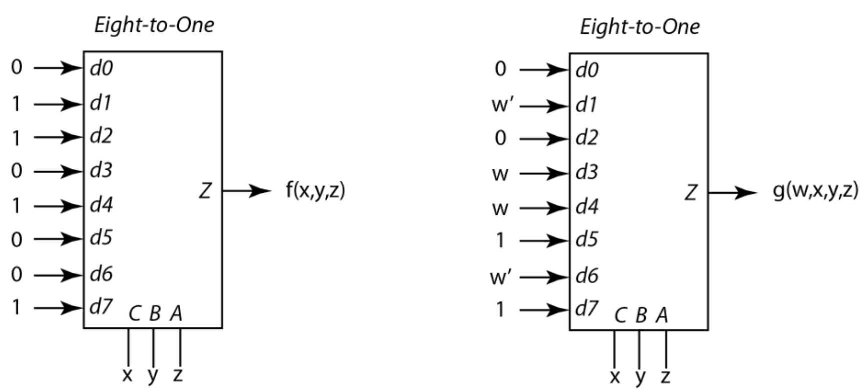
Hands-On Exercises for Homework and In-Class Assignments

The low-cost and portability of The BitBoard makes it feasible to assign homework and in-class problems requiring hands-on solutions. Table 3 lists exercises that have been designed for these scenarios. The assignments have been formulated to use minimal devices and wiring so they can be completed in a short period of time. Two sample assignments are illustrated below. Lessons learned using these and other exercises are mentioned below and will be further discussed in the conference presentation.

Table 3 – Homework and In-Class Assignments Using The BitBoard

Concept	*Assignment*
Gate-level circuit equivalence	Derive an experiment to show circuits are logically equivalent.
Decoders	Realize a full-adder using a decoder and gates.
Multiplexers	Realize a logic function using multiplexers and gates.
Counters	Realize basic counters using flip-flops and gates.
Mealy and Moore machines	Study Mealy and Moore machines.
Equivalent states	Derive an experiment to show that two FSMs are equivalent.

Multiplexers – Multiplexers are usually described as many-to-one, typically 2^n to 1, selectors where the *n* control signals are used to specify which of the input data lines defines the data output. Multiplexers can also be used to realize a combinational logic function by associating input variables with the control signals and tying each data line to logic 1 or logic 0 as necessary to produce the proper output for a given input pattern. Students are asked to wire the two circuits shown in Figure 5 and to experimentally derive truth tables for the functions realized. Generic eight-to-one multiplexers are shown in the figure but SN74151s are actually used. This assignment helps students learn how multiplexers work and also demonstrates how they can be used to realize logic functions.

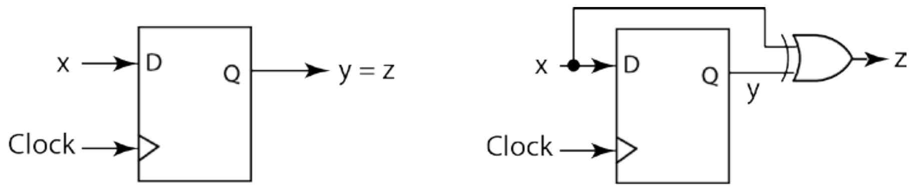


(a) Three-Variable Function (b) Four-Variable Function

Figure 5 -- Multiplexer Assignment

Mealy and Moore Machines – Students often have difficulty understanding the difference in Mealy and Moore models of finite state machines. This assignment involves wiring the two circuits in Figure 6 and experimentally deriving, in parallel, their response to the input sequence

0-1-0-1. Comparing the responses illustrates how the output timing differs between the two circuits.



(a) Moore Machine (b) Mealy Machine

Figure 6 -- Mealy and Moore Machines

The circuit equivalence, multiplexer, and Mealy/Moore exercises were included in homework assignments for the spring 2016 offering of the course. Anecdotal feedback suggests that they helped students better understand the concepts being covered. These assignments and more will be incorporated in homework for future offerings of the course.

Plans to use The BitBoard for in-class exercises proved problematic due to classroom constraints. More specifically, desk-top surfaces were too small and access to power was inconvenient. The latter can be easily overcome using batteries but the former requires new desks or a different room making it more than a technology or logistics problem.

Observations and Student Feedback

The BitBoard and The BitBox have proven to be effective and reasonably easy to use. Initially, students had some difficulty placing jumper wires from the header sockets (B and C) to the solderless breadboards. This became less of a problem as they gained experience. Some students had difficulty learning how to use the solderless breadboards themselves. However, this is a more general problem and not specific to The BitBoard.

The reliability and ruggedness of The BitBoad was an initial concern which proved to generally be unwarranted. Three BitBoards were found to have soldering problems and were quickly repaired. Wires were broken off inside of header sockets on two BitBoards requiring replacement of the headers. Some connectors separated from the ribbon cables and had to be replaced. Failures such as these, though minor, do frustrate and impact students. However, the impacts were minimized by having spare boards and cables to replace those needing repair.

A survey of students' experiences using The BitBoard and The BitBox was conducted in the fall 2015 semester and will be repeated in spring 2016. Results of the fall survey are summarized in Figures 7 and 8 and discussed below. The results will be updated in the conference presentation.

Response to questions 1 and 2 strongly suggest that The BitBoard and take-home lab kit were pedagogically effective. Question 3 focused on the educational value of wiring circuits and the results suggest it is although some students were neutral on the question. The ease of use and reliability of The BitBoard are addressed in questions 4 and 5. Eighty percent of students either agreed or strongly agreed that The BitBoard was easy to use while the remaining were neutral. This is considered an acceptable response since students often have difficulty using solderless breadboards. About twelve percent of students thought The BitBoard was not reliable and a similar number were neutral on the question. This is not considered to be an acceptable level of reliability and is somewhat surprising given the few failures that were actually reported, as discussed above. Nevertheless, all BitBoards were thoroughly retested before issuing them to students for the spring 2016 semester and any subsequent failures will be appropriately addressed.

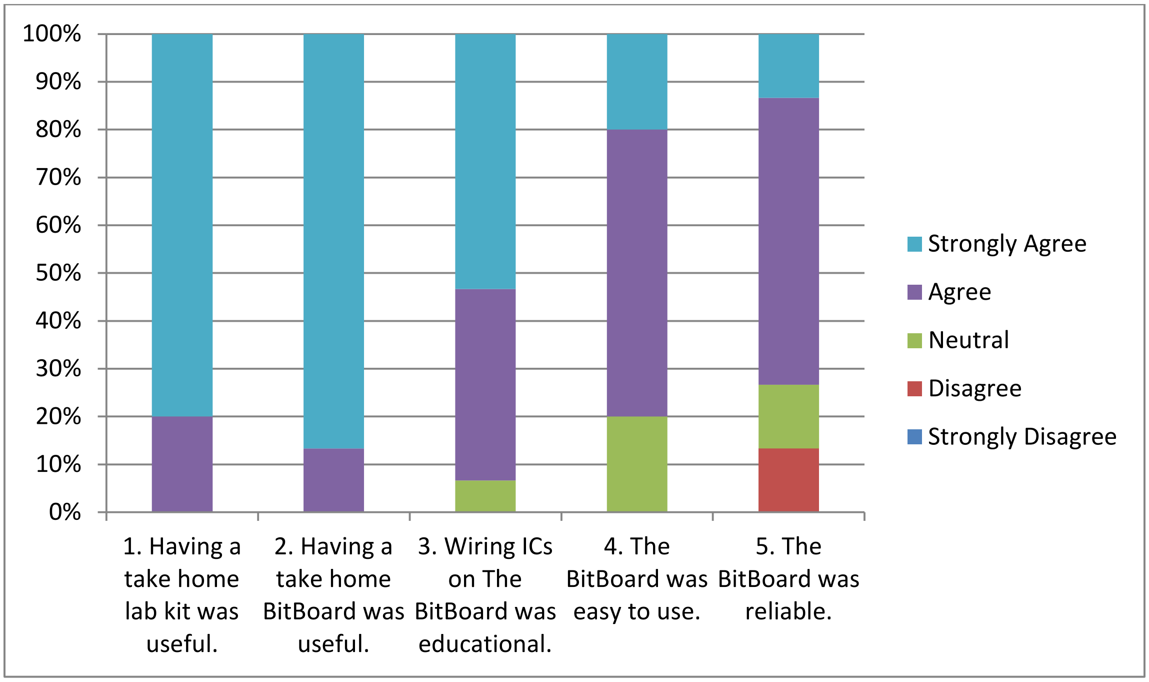


Figure 7 – Student Survey Results

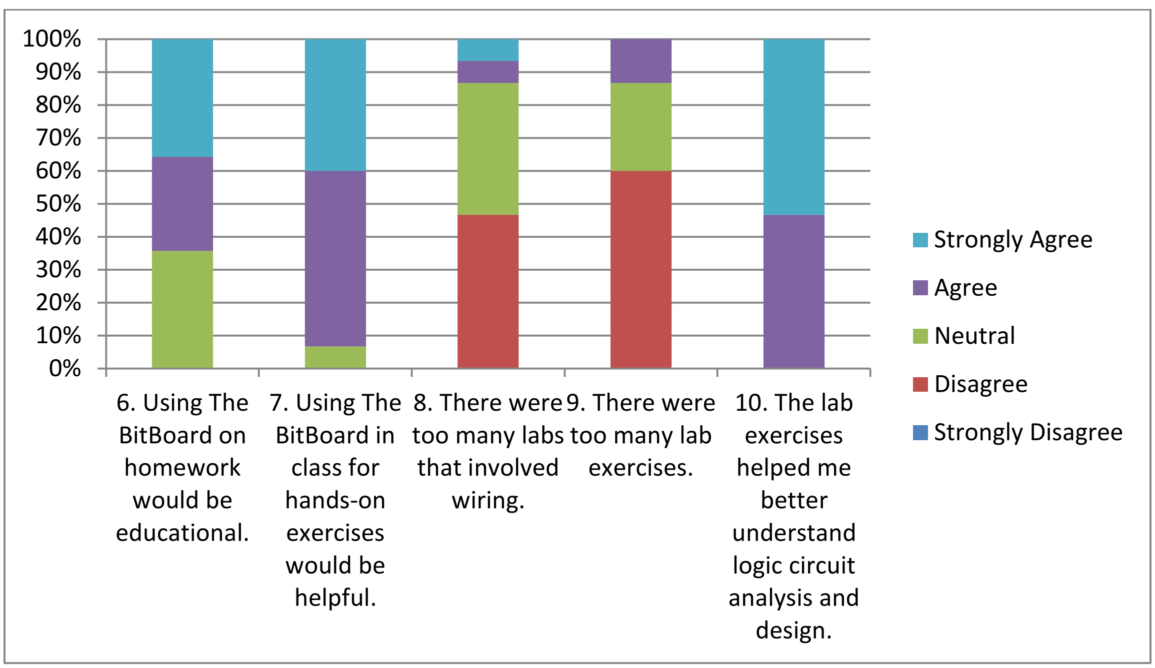


Figure 8 – Student Survey Results (con't)

Questions 6 and 7 are concerned with the use of The BitBoard on homework and for hands-on exercises during class. All students are either neutral, agree, or strongly agree that such exercise would be useful. However, students appear to favor in-class over homework usage. Responses to questions 8 and 9 suggest there are too many wiring labs and perhaps too many labs. This will be investigated further after spring 2016 results are available. Most importantly, question 10 responses indicate that all students either agree or strongly that the laboratory exercises helped their understanding of logic circuits.

Conclusions and Future Plans

The BitBoard coupled with the DE1 has proven to be an excellent replacement for the IDL-800 that was previously used in the laboratory. Some of the benefits of the change are as follows.

- The BitBoard is much less expensive than the IDL-800 ($60 versus $400+)
- The BitBoard enables portability not possible with the IDL-800
- The DE1 provides more slide switches and LEDs than the IDL-800
- The DE1 seven-segment displays are easier to use than those on the IDL-800
- The BitBoard is easier to repair than the IDL-800

Useful features of the IDL-800 that are not provided include the Digital Voltmeter (DVM) and the Function Generator.

Future plans include interfacing The BitBoard to the Altera DE0-CV. This will require writing a new Verilog interface program for the DE0-CV Cyclone V FPGA but should not require any changes to The BitBoard hardware or cabling. Other plans include the possibility of adding more header sockets to provide redundancy and easier wiring, exploring ways to lower the cost of both The BitBoard and The BitBox, finding options for providing DVM and function generator capability on The BitBoard and/or in The BitBox. Finally, additional exercises for using The BitBoard in laboratory, homework, and in-class settings will be developed.

References

1. *DE1 Development and Education Board, User Manual*, Altera Corporation, 2006.
2. *DE0-CV Development and Education Board, User Manual,* Altera Corporation, 2015.
3. *Quartus II Introduction Using Verilog Designs*, Quartus II Web-Edition Version 13.0. Altera Corporation. May, 2013.
4. Bill D. Carroll, David Levine, and Shawn N. Gieser, “A Hierarchical Project-Based Introduction to Digital Logic Course,” 2014 ASEE Annual Conference, June 15-18, Indianapolis.

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