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Deploying Adaptive Learning Environments to Overcome Background Deficiencies and Facilitate Mastery of Computer Engineering Content

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Abstract

This paper describes the use of web-based adaptive learning modules to improve student mastery of computer engineering concepts. Adaptive learning is an exciting pedagogical approach that can provide individual instruction to students by dynamically altering the difficulty of content based on an ongoing assessment of the students' capability. This technique has recently become practical for large groups of students due to advances in course management systems. The computer-based adaptive material can guide a student through a set of incrementally difficult exercises. This has been shown to be nearly as effective as a live instructor guiding the student through the material. What makes computer-administered adaptive learning appealing is that it can reach an expansive student body. This provides a broader reach than can be achieved by instructor-administered guidance, which is limited by the instructor's availability. Another potential impact of adaptive learning is tailoring the material to the demographics of the students. This can be as simple as the wording used in the problem or posing the problem as a relevant example of interest to a particular student group. This approach has the potential to enhance student perception of the value of the content. This leads to increased content retention and improves student motivation to excel in the course. This paper will discuss the work being conducted at Montana State University in developing and deploying adaptive learning modules at a diverse set of universities to collect data on how different student groups use and are impacted by the materials.

1. Background

1.1 Using E-Learning Environments for the Delivery of Engineering Course Content

There has been a considerable amount of research into the effectiveness of using e-learning environments for the delivery of engineering coursework over the past two decades. The authors of [1], [2] and [3] present an analysis of the potential benefits of web-based engineering education highlighting that e-learning can increase access, diversity, collaboration and lifelong learning. A report to congress by the Web-based Education Commission [4] demonstrated the ability of web-based education to center learning around the student instead of the classroom and provide continuous, relevant training. This has the potential of providing a customized learning environment, which improves learning and reduces withdrawal and failure rates. Web-based education has also been shown to broaden participation of non-traditional students. A recent U.S. Department of Education meta-analysis of 176 online learning studies drew several important conclusions relating to past evidence-based reports of web-based learning, including that non-traditional students actually performed better on average than those learning the same material through traditional live-taught lectures [5].

The potential advantages of web-based learning are widely accepted but also predicated on the notion that online learning needs to achieve the same level of *quality* as traditional live instruction. The authors of [1] and [6] present metrics for evaluating the quality of web-based education, which include learning effectiveness, student satisfaction, faculty satisfaction, access and cost effectiveness. While metrics such as access and cost can be quantitatively measured, metrics such as satisfaction and effectiveness are more difficult to gauge and are most commonly studied through individual, content-specific experiments. A 2010 report to the Department of Education described a variety of studies comparing web-based to traditional delivery and found that the content matter of the course played an important role in the effectiveness of learning [7]. There have been individual studies of specific courses comparing online to live delivery. The authors of [8], [9] and [10] compare the results of different delivery techniques for introductory courses in economics, psychology and business. The authors of [11] and [12] compare the results of different delivery techniques for engineering-specific courses in computer graphics and electrical circuit analysis. While the authors of [13] and [14] attempt to form a general consensus of student perception of online delivery by averaging data from many different types of courses, the majority of literature in this area concedes that not all topics are equal with respect to their effective online delivery. Topics that require equation manipulation and iterative discussion, for example, are most difficult to deliver [15] despite advances in computer-based tools. For an instructor wishing to convert a course to web-based delivery, there is a set of accepted best practices based on sound pedagogy that should be followed as presented by the authors of [16], [17] and [18]; however, the instructor would also need to review case studies of web-based versus live delivery for the specific content matter being taught.

1.2 Web-Based Delivery of Engineering Laboratory Experiments

Delivering the laboratory component of an engineering course online has been identified by a number of research groups ([1], [3], [19] and [20]) as the largest barrier to widespread penetration of web-based courses across the curricula in higher education. The importance of a laboratory experience is often inherently accepted by instructors as a way to reinforce classroom concepts; however, there has been a considerable amount of research as to why a laboratory experience is important and what students gain from it. The authors of [20] provide a comprehensive and historical accounting of the purpose of a lab experience in engineering education. The authors present that a lab gives students exposure to learning across multiple knowledge domains including cognitive (instrumentation, modeling, experimentation, data analysis and design), psychomotor (manipulation of an apparatus), sensor awareness and affective/cognitive (learning from failure, creativity, safety, communication, teamwork and ethics) [20]. The quality of a remote laboratory experience should meet the standards and criteria of a traditional hands-on experience if effective learning is to be achieved [21].

There are a variety of mechanisms to provide a remote laboratory experience in distance education. The author of [22] provides a survey of remote lab technologies that includes virtual laboratories (e.g., model-based web simulations), remote laboratories (e.g., real control of equipment and devices located elsewhere) and a hybrid of the two. Some engineering labs are amenable to portable kits that students can transport and use to conduct the experiments completely outside of the university facility. Portable laboratory kits provide the greatest flexibility, but are often cost prohibitive. For example, the National Instruments Elvis [23], a popular portable lab kit, has a starting cost of $2,600. This is comparable to a full semester's worth of tuition at MSU, and far too costly for adoption at public universities and community colleges. The authors of [24] reported on the state-of-the-art of virtual labs and concluded that while virtual labs provide students with the ability to run the experiments on their own computers at any time, they also require considerable development time and often encounter integration issues. The authors of [25] and [26] present technologies for remote laboratories for electrical engineering topics that demonstrate custom systems for performing laboratory experiments at a distance. Both [25] and [26] report an increase in student access while being able to teach real measurement techniques. For instructors administering laboratories that teach measurement techniques using industrial-grade test equipment, a remote laboratory approach is the preferred solution. For content that is amenable to a portable lab kit, and cost can be minimized, this approach is preferred to provide flexibility and access.

1.3 Web-Based Adaptive Learning

One of the challenges that instructors of introductory-level college courses face is matching the difficulty of the content with the capability of the students. What makes this even more challenging is that every course has a range of student capability. Instructors envision themselves working with the best and brightest students, challenging them to pursue advanced concepts that spur original thought and promote inquiry. In reality, instructors discover that the overall course material must be tailored for the mean capability of the class. If the course material is too difficult in order to challenge the top performing students, 90% of the class is left lost and confused. If the course material is too easy in order to accommodate students with minimal preparedness in the area, the majority of students are left bored and uninterested. As a result, instructors must tailor the difficulty of the material to the mean capability so that the majority of the students are able to learn. A further reality is instructors tend to spend most of their time working with the lowest performing students to bring them up to speed with the mean level of the class. This leaves the majority to fend for themselves and the top students unchallenged.

Adaptive learning is an exciting pedagogical approach that can provide individual instruction to students by dynamically altering the difficulty of content based on an ongoing assessment of the students' capability [27,28]. This technique has recently become practical for large groups of students due to advances in course management systems. The computer-based adaptive material can guide a student through a set of incrementally difficult exercises. This has been shown to be nearly as effective as a live instructor guiding the student through the material [29,30]. What makes computer-administered adaptive learning appealing is that it can reach an expansive student body. This provides a broader reach than can be achieved by instructor-administered guidance, which is limited by the instructor's availability.

2. Adaptive Learning Module Design

2.1 Course Material Design

The adaptive learning course materials being developed at Montana State University are for a sequence of digital logic courses found in every accredited computer engineering program in the U.S. Since the materials are deployed most broadly in this project using the existing courses at MSU-Bozeman, the MSU course names and numbers are used to describe the content for the remainder of this paper. The two courses that are impacted by this project are *EELE 261 – Introduction to Logic Circuits* and *EELE 367 – Logic Design*. EELE 261 is a four-credit course based on the semester system. The workload for this course consists of 3 credits of lecture and 1 credit of laboratory. This course is required of all students pursuing baccalaureate degrees in electrical (EE) and computer (CpE) engineering. This course is commonly taken for professional elective credits by computer scientists, mechanical engineers and physics students. This course only requires knowledge of algebra so it is often taken by freshman students. This also makes it an ideal course for community college deployment since it does not require calculus, which is often the largest obstacle for community college students getting started taking discipline specific classes toward a 4-year STEM degree. This course covers the introductory material associated with classic digital logic design (70%) and then introduces hardware description languages (HDLs) as a launching point to the process of modern digital design (30%). The learning objectives for this course are as follows:

1) Describe the difference and advantages/disadvantages of analog versus digital systems.
2) Describe numbers system formation (decimal, binary, hexadecimal) including signed numbers and perform conversions between.
3) Describe the underlying circuitry used to implement logic gates and successfully interface devices while meeting specifications relating to DC operating conditions, switching characteristics, power supplies, and maximum output current specifications.
4) Describe the combinational logic design process including the Boolean algebraic framework and how to apply its rules to the synthesis, minimization and manipulation of logic circuits.
5) Describe the history, role and basic constructs of a hardware description language (HDL) and use an HDL to design and simulate combinational logic circuits.
6) Describe the behavior of medium scale integrated circuits (MSI) and use them in the design of complex combinational logic circuits.
7) Describe the behavior of sequential logic and synthesize finite state machines.

EELE 367 – Logic Design is a four-credit course based on the semester system and has a pre-requisite of EELE 261. The workload for this course consists of 3 credits of lecture, and 1 credit of laboratory. This course is required of all students pursuing baccalaureate degrees in computer engineering and is a professional elective for electrical engineering students with a digital systems interest. This course covers modern digital design using hardware description languages. The learning objectives for this course are as follows:

1) Describe the full modeling capability of a Hardware Description Language.
2) Use the full capability of an HDL to design digital systems including combinational logic and finite state machines.
3) Describe the architecture of modern programmable logic devices and semiconductor memory.
4) Describe the operation of arithmetic circuitry and design with an HDL.
5) Describe the essential components of a computer system.
6) Design a computer system using an HDL.

The adaptive learning system being developed in our work fall into three primary categories: skill development tasks, formative assessment, and summative assessment. For the skill development tasks and formative assessment, four levels of competency are defined: deficient, beginner, competent and advanced. Learning activities exist (both tasks and formative assessment) that correspond to these levels in order to facilitate the adaptive learning approach.

Skill development tasks are items that are assigned to the students in order to increase their level of understanding of a topic. Skill development tasks consist of reading assignments in HTML format and/or print textbook, instructional videos using the Camtasia Relay Screen Capture tool [41], working practice problems with solutions provided, and performing laboratory exercises. Videos and reading assignment tasks are used to develop cognitive skills. Practice problems are used to develop affective skills. Laboratory exercises are used to develop both affective and psychomotor skills. Each task corresponds to one of the four levels of competency defined above.

Formative assessment is accomplished using automatically scored quizzes within the course management system. For each level of competency, a statistically large number of quiz questions is created. When a student is assessed, the tools are pulled from the large pool in a randomized fashion. This addresses academic dishonesty, which is a significant concern for web-based courses. Quiz questions are created for each of the learning modules that assess multiple knowledge domains at each of the four levels of competency. Cognitive skills are assessed using auto-graded multiple choice questions. Affective skill assessment are measured using a combination of auto-graded multiple-choice questions, auto-graded circuit analysis questions with numerical entry fields and uploaded circuit design files. The automatically graded questions are implemented in a generic text-based file format, which can be imported into any course management system. The questions are developed based on widely accepted concept inventories for computer engineering courses [31-34]. Figure 1 shows the environment that facilitates the skill development and formative assessment for these course.

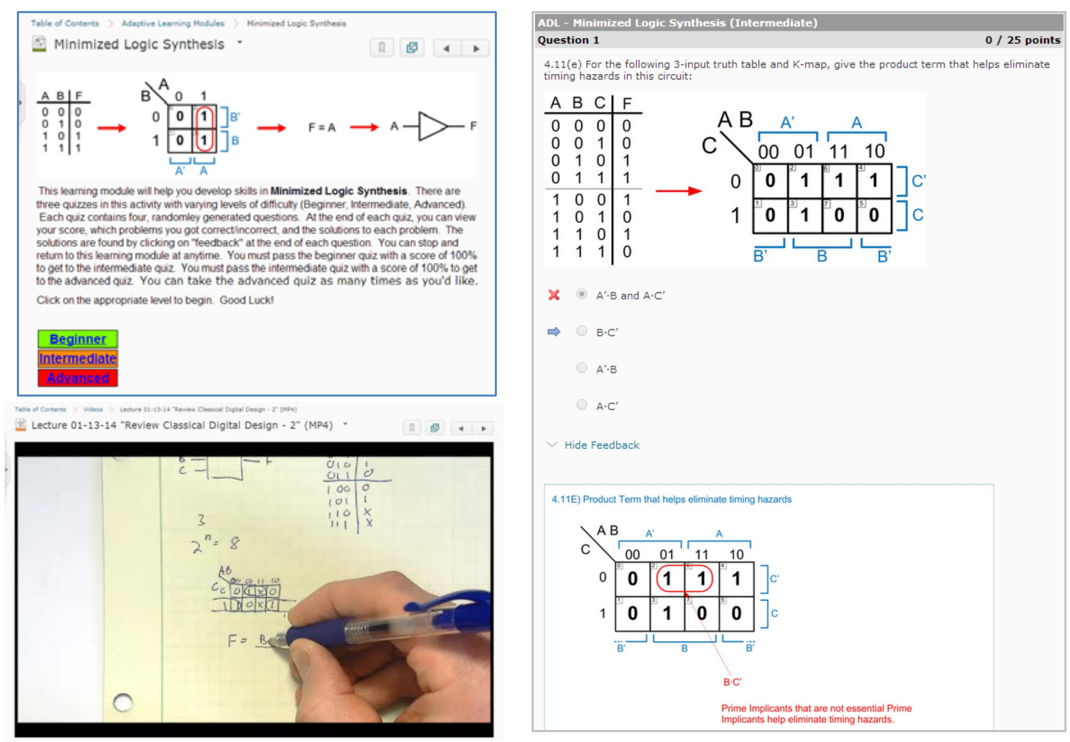

Figure 1. Adaptive Learning Environment for Skill Development and Formative Assessment.

Summative assessment is performed at the end of each learning module through an automatically graded exam administered in the course management system. Students are notified of their score on each module exam.

The adaptive learning algorithm is shown in the following flow chart. For each learning outcome, an initial set of tasks is assigned (e.g., videos, reading assignments, practice problems, lab exercise). These tasks represent the traditional items that are assigned in a course without adaptive learning. An initial assessment quiz is given to measure the level of student understanding. The performance on this assessment will determine the current level of understanding and put the student into one of the four levels of competency (e.g., deficient, beginner, competent and advanced). Students categorized as *deficient* are given a series of additional tasks to build their background information. An interim quiz will then be given to determine if they are ready to move into the *beginner* category. If they are, they then must complete a set of tasks at the *beginner* level. If they are not deemed ready, they are given additional *deficient* level tasks. This iterative process continues until the student passes the interim quiz and moves into the beginner category. The same process is used for students in the beginner category with the exception that the tasks are at the *beginner* level and the interim quiz assesses whether they are ready to move into the *competent* category. Students deemed competent by the initial quiz (or reaching competence by working through deficient and/or beginner level tasks) are qualified to take the module exam. Students may optionally choose to receive more training at the *competent* level. Students deemed *advanced* by the initial quiz (or reaching advanced by working through competence level tasks) will also be qualified to take the module exam or do optional training at the advanced level. This process provides inherent formative assessment and tracks the progression of each student as they learn the content matter. All interim quizzes used for formative assessment are ungraded and exist to dynamically adapt the difficulty of the material and track student progression. It is at the discretion of the instructor if the module exams count toward the students' course grade.

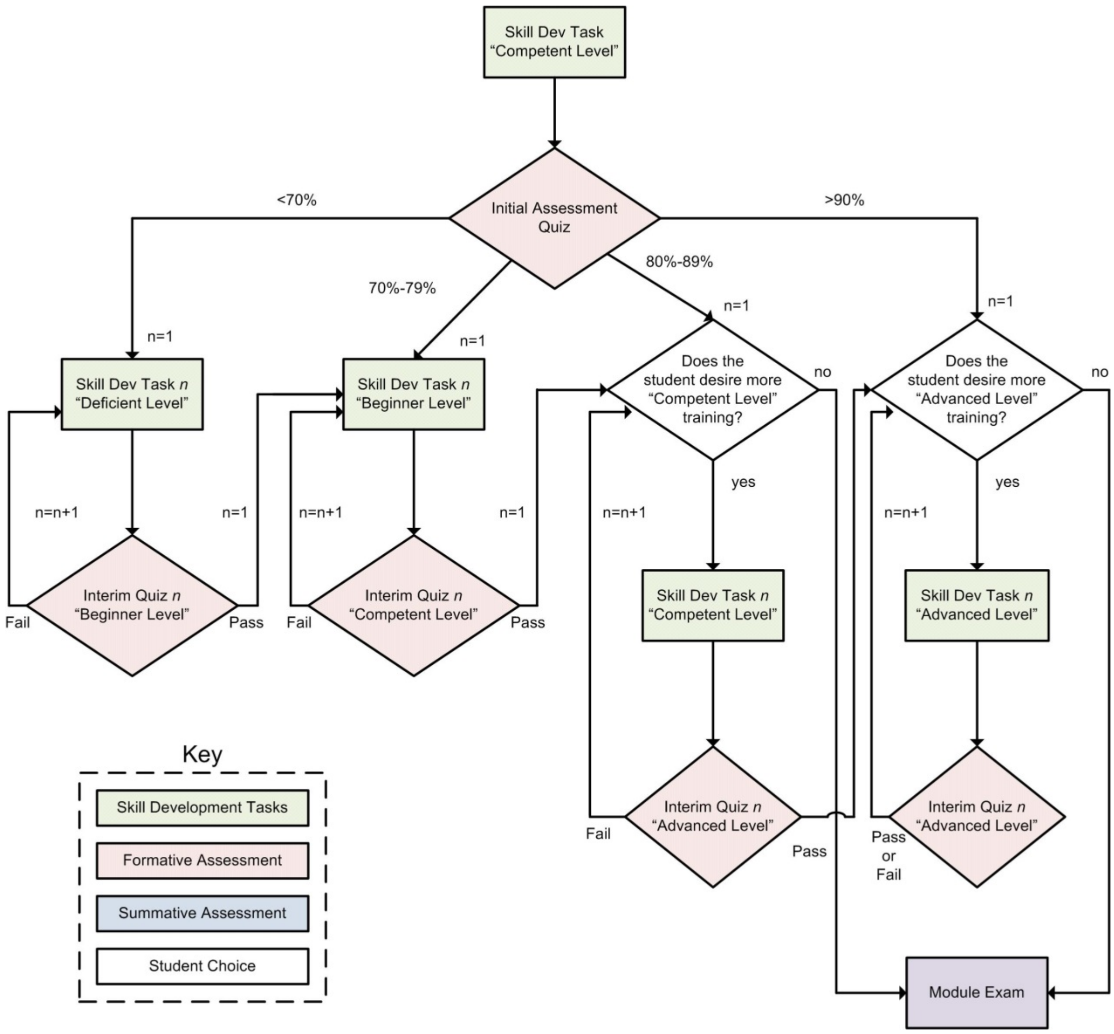

Figure 2. Adaptive Learning Algorithm.

The following table lists the topic of each adaptive learning module that are being used in this work. For each learning outcome of the two courses, there are between 1-4 adaptive learning modules. Each module contains between 10 to 40 automatically graded quiz questions for use in formative assessment and another 10 automatically graded questions for use in the module exam. Each module contains reading assignments, instructional videos, and lab exercises. Effort is taken to develop the materials so that they can be imported into any course management system [40].

Course	Learning Outcome	Adaptive Learning Module
EELE 261	1 - Analog v.s Digital	1a - Advantages/Disadvantages
	2 - Number Systems	2a - System Formation 2b - Conversions 2c - Signed Numbers
	3 - Digital Circuitry	3a - Basic Gates 3b - Operating Conditions & Interfacing 3c - Logic Families 3d - Driving Loads
	4 - Combinational Logic Design	4a - Boolean Algebra Framework 4b - Logic Synthesis 4c - Logic Minimization 4d - Timing Considerations
	5 - HDLs	5a - History & Role in the Design Flow 5b - HDL Constructs 5c - Modeling Concurrent Behavior
	6 - MSI Logic	6a - Basic Building Blocks
	7 - Sequential Logic	7a - Storage Devices 7b - Timing Considerations 7c - Finite State Machines 7d - Counters
EELE 367	1 - Advanced HDL Capability	1a - Modeling Sequential Behavior 1b - Add On Packages 1c - Test Benches / Standard IO
	2 - Modern HDL Modeling	2a - Combinational Logic 2b - Sequential Logic 2c - Finite State Machines
	3 - Programmable Logic / Memory	3a - PLDs, FPGAs 3b - SRAM, DRAM & FLASH
	4 - Arithmetic Circuitry	4a - Adders / Subtractors 4b - Multiplication 4c - Floating Point Operations
	5 - Computer Architecture	5a - CPU, Memory, IO 5b - Instruction Sets 5c - CPU Components 5d - Bus Topologies
	6 - Computer Design	6a - Instruction Set & CPU Design 6b - Memory Design 6c - Bus Design 6d - IO Design

Table 1. Details of Content Subjects and Associated Adaptive Learning Module.

2.2 Laboratory Material Design

Lab exercises are also used in each course, which correspond to the learning outcomes listed in Table 1. These exercises are used as skill development tasks in the adaptive learning algorithm and are also designed with 4 levels of difficulty just as the reading, videos, and formative assessment questions. The exercises are designed for implementation on a portable lab kit that that minimizes cost. The selection criteria for the lab kit are as follows:

- **Cost <$250**. This allows kits to be checked out to students and the kits to be maintained (e.g., wear and tear) using existing program fees.
- **Provides Interfacing Experience**: Students need to develop the interfacing experience that comes with using discrete parts and a breadboard. This indicates that a single off-the-shelf board by itself is insufficient to meet the learning objectives of these modules.
- **Provides Programmable Logic Experience using HDLs**: Students also need to gain experience with the modern digital design flow using HDLs and programmable logic.
- **Fully Portable:** This allows the student to conduct the labs at any location without the need for specialized, stationary lab equipment. All circuitry must be powered using a widely available supply (e.g., USB).
- **Provides Measurements Experience**: Students need to be able to take simple electrical measurements such as voltage, current and timing measurements.

An extensive survey of available technology to meet these criteria was conducted in 2014 to meet each of the above criterions. To provide experience with discrete logic and interfacing, students will use a standard breadboard and a kit of basic logic gates from the 74HC logic family in addition to standard IO (LEDs, buttons, etc.). The expected cost of this kit is ~$25. To provide experience with the modern design flow, the *Altera DE0-nano* board is used [42]. This board contains a Field Programmable Gate Array (FPGA) that allows students to design digital systems in an HDL and download their designs to the board. The cost of the DE0-nano board is $59. The DE0-nano is powered from any USB connector and the design software (Altera Quartus II) is provided free of charge from Altera. This allows both a power supply to be provided to the DE0-nano in addition to design downloading using a single USB connection. The DE0-nano also provides interfacing pins so that the FPGA can interface with discrete parts on a breadboard. Additionally, the DE0-nano provides a +3.4v supply (up to 200mA) that can be used to power the students' breadboard and discrete parts, thus eliminating the need for any external power other than a connection to a USB port. Measurement capability is provided using the *Digilent Analog Discover USB-Oscilloscope* [43]. This measurement platform is powered through a USB connection and displays electrical measurements using software provided with the device. The Analog Discover provides an oscilloscope, voltage and current measurements, a signal generator and a logic analyzer. This system costs $99. Finally, students conducting the more advanced exercises associated with the EELE 367 will use a DE0-nano expansion header to provide more basic IO compared to what comes standard on the DE0-nano board itself. This expansion header costs $60 and was designed at MSU. The total cost of this full lab kit is **$243**. The following figure show the use model for this equipment in the learning modules associated with EELE 261 and EELE 367.

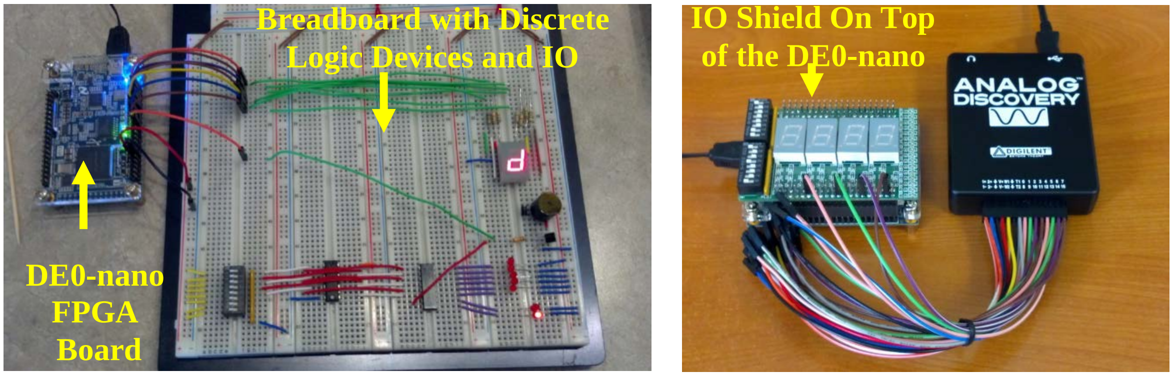

Figure 3. Portable Lab Kit Selected For the Adaptive Learning Modules.

3. Preliminary Results

The described learning modules and associated assessment will be deployed in the next two years across diverse range of universities and colleges in Montana. In order to gauge the impact of the approach, a pilot study was conducted at Montana State University on adaptive learning modules for the sophomore level course (EELE 261). As part of this investigation, our team created two adaptive learning components, one on canonical logic synthesis and one on minimized logic synthesis, two core concepts within digital logic design. The modules were offered as optional, ungraded supplementary exercises for students taking EELE 261 in the fall of 2013. In this adaptive learning exercise, students were provided learning materials in the form of reading assignments and instructional videos. The students then started formative assessment by taking a quiz with a beginner level of difficulty. The quiz consisted of 4 questions randomly pulled from a pool of 25 questions on the concept, each with the same level of difficulty (e.g., beginner). If the student passed the quiz, they were permitted to continue to the intermediate level in which another quiz was administered, but this time with questions with a higher level of difficulty. Upon passing this quiz, the students continued to the advanced level where a final quiz was administered. Students could take the quizzes at each level as many times as they wished, but could only move onto the next level of difficulty once they had passed the prior level with a score of 100%. When a student missed a question, the solution to the problem was presented. In this way, the students could work through problems and get automated assessment of their ability.

Our team collected background information on the students that included major, gender, ethnicity, current GPA, current number of college credits obtained, and current grade in the class. The information was encoded and used as covariates in an assessment as to whether the adaptive learning modules helped the students, if certain groups of students chose to use the modules more than others, and whether the modules helped certain groups of students more than others. Of the 70 students taking the introductory digital logic course, 60% chose to use the adaptive learning modules. It is recognized that self-selection creates bias is the assessment of how much the modules helped learning, however, self-selection allowed the experiment to see whether certain groups chose to use the modules more than others. A variety of interesting outcomes were discovered through this mini-experiment. First, 16% of the students who chose to use the adaptive learning modules performed higher on the exam that covered the material in the modules as compared to their other exam scores that did not have adaptive learning modules available. Second, the students that chose to use the modules and benefited the most (as measured by their subsequent exam scores) had GPAs between 3.0-3.5. It was discovered that students with GPAs below 3.0 and above 3.5 were less likely to use the modules compared to students with GPAs between 3.0-3.5. There was an insufficient number of under-represented minorities in the class to form any conclusions on the influence of gender or ethnicity (1 Native American, 2 Female). A survey was administered after the exam covering the material in the adaptive learning modules and 86% said they would use the modules to help them understand complex material if they were available throughout the course. While the sample size of this study was small, it did provide two findings that are further motivation for the proposed work. First, it is possible to develop and deploy an adaptive learning system using a standard course management system (e.g., Desire2Learn) and that the majority of the students wanted more adaptive learning exercises.

4. Future Work

The next phase of this work is to develop the entire suite of adaptive learning modules across all subjects and learning outcomes. These will be then deployed across a diverse set of schools. This will allow assessment data to be collected over a larger statistical sample. The results will then be correlated to the demographic information for the students in order to identify any patterns that emerge on how certain groups use and are impacted by the adaptive learning approach. The adaptive learning modules will then be modified to try to increase performance of certain groups by rewording the problems to make the concepts more relevant to the particular group. The differently worded problems will be automatically administered through the adaptive system.

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