A Personalized Learning System to Address Background Deficiencies and Highlight the Value of Digital Logic

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Abstract: This paper presents the development of a novel, web-based, adaptive learning system to teach digital logic. The system provides personalisation of learning by adapting the material to the competence level and interests of the student. The system is based on an automatic adaptive learning strategy that contains banks of online quiz questions of varying difficulty. As students answer questions correctly they are given more challenging questions. If students answer questions incorrectly, they are given easier questions. The current competence level of the student is determined by their performance on these questions and the corresponding level of course material is then presented. In this way, students that require additional time on foundational material can build competence on their own while students that excel at the material can move toward advanced concepts more rapidly. We build upon this system by considering the demographics of the student in order to make the material more relevant to the user. Research in the field of social psychology has shown that the choice of application to illustrate the engineering concepts can dramatically increase interest in the subject by certain student demographics. An e-learning environment provides a unique opportunity to reinforce the application of the material since the student is engaged with the system already. This paper describes the development of our system, the data collected to measure baseline student understanding, a pilot study of a small-scale implementation of the adaptive learning system, and the future plans to include demographics specific applications of the material.

Keywords: Engineering education, adaptive learning, personalized learning, student motivation, retention, professional formation

1. Introduction

The use of technology-based instruction is revolutionizing pedagogical practices in higher education (Enriquez, 2010, Figlio, 2010, Means, 2010). In the past decade, there has been a rapid advance in the number and quality of tools available to create multimedia course content and develop automated assessment measures. This has allowed instructors to move lower levels of learning such as knowledge-transfer and comprehension outside of the live lecture period and use in-class time to focus on higher order learning. This has also allowed instructors to create formative and summative assessment tools that can be automatically graded by course management systems. This reduces the amount of time that instructors have to spend grading and allows them to focus more on working with students and developing course content. The *flipped classroom* is the classic example of this type of educational revolution enabled by technology (Bishop, 2013).

While spending class time and instructor focus on higher order learning is the desired allocation of resources, it magnifies background deficiencies of some students. This is especially apparent in introductory-level courses where college preparedness can vary widely. Students with background deficiencies are often ill-equipped to learn lower level skills on their own using multimedia course content such as videos or web-based tutorials. They also may lack the pre-requisite knowledge to comprehend the new material on their own. This leaves struggling students with no support as higher education moves more heavily toward flipped classrooms and problem-based learning (Aydin 2016). This creates an ironic scenario in which technology-enhanced instruction actually widens the gap between adequately prepared students entering college and those with background deficiencies. However, the solution to this issue can also be addressed with technology through a personalized learning environment to specifically target the student's deficiencies and automatically guide them through activities to bring them up to proficiency. This type of personalized, *adaptive learning system* has the potential bring up the ill-prepared students to a proficient level without using precious instructor time (Brusilovsky, 2003, Munoz-Merino, 2011).

One of the exciting aspects of deploying a personalized learning system is that the students are already engaged within the environment so additional educational components can easily be added. The obvious component that this systems can include is advanced material for the higher performing students. An initial assessment of understanding can be administered to determine whether a student is either deficient or proficient. Those that are deemed immediately proficient can bypass the activities to address deficiency and can engage in content that targets higher order thinking. Another exciting aspect of a personalized learning system is the ability to stress the *affective* learning domain. This may include stressing the application of the material or demonstrating the relevance of it in modern society. Research in social psychology has shown that the *value* of a profession is a predictor of motivation to persist in the degree for certain student demographics. It has been shown that underrepresented minorities and first generation college students are more motivated to pursue and persist in professions that are seen as having *communal* value, or ones that help others and/or community (Smith, 2007, Seymour, 1997, Metz, 1999). This line of research has also shown that the interventions needed to show that a profession has communal value are relatively straight forward to implement. Something as simple as using an application that inherently *helps others* in examples and homework problems can have a large impact on a student's impression about the profession (Metz, 2011). This is especially effective if the communal value of the material is stressed repeatedly throughout the course. A personalized learning system has the potential to dynamically change the type of application used to teach the concept to match the background of particular students in addition to continuously reinforcing the value of the profession to society. This allows the affective learning domain to be stimulated without using instructor resources.

This paper presents an overview of a personalized learning system that is in development at Montana State University (MSU) that focuses on a set of introductory-level digital logic courses. This system is part of a long term project to deploy a nationwide, e-learning system to address background deficiencies of incoming freshman, facilitate mastery for top performing students, and include demographic-specific applications in order to stimulate the affective learning domain. This system will stress the communal value of the content in order to improve motivation of underrepresented minority students and first generation college students to persist in computer science and engineering. This paper presents the development of a detailed set of learning objectives that have been developed for digital logic in addition to the measures used to collect a baseline of understanding prior to the implementation of the adaptive learning algorithm. We then present the algorithm itself and a pilot study of the system for one of the learning outcomes that had the lowest level of performance in the baseline. Finally, we present the approach that will be used to stimulate the affective learning domain by using *Everyday Examples of Engineering (E^3)* (Metz, 2011).

2. Method

2.1 Learning Outcomes for Digital Logic

The first step in the development of the personalized learning system was to create a set of specific learning outcomes to be measured. The learning outcomes were developed to cover a sequence of two courses in digital logic at the sophomore and junior level. One or both of these courses are required in most ABET accredited undergraduate degrees in the U.S.A. Since these courses are widely used, there is a general consensus about the type of content that is typically covered in them (Herman, 2010, Goldman, 2010). Figure 1 shows the 55 specific learning outcomes developed for teaching digital logic at an introductory level. The outcomes are grouped into 13 modules, which each represent an overarching learning *objective*. Modules 1-7 are typically covered in a 200-level course and modules 8-13 are typically covered in the 300-level course, although delivery approaches may vary at different universities.

Learning Objective	**Learning Outcome**	**Learning Category**					
The overall learning goal of this module is to:	*After completing this module, a student will be able to:*	**1**	**2**	**3**	**4**	**5**	**6**
Module 1: To understand the basic principles of analog and digital systems.	**1.1:** Describe the fundamental differences between analog and digital systems.	x					
	1.2: Describe advantages of digital systems compared to analog systems.	x					
Module 2: To understand the basic principles of binary number systems.	**2.1:** Describe the formation and use of positional number systems.		x				
	2.2: Convert numbers between different bases.			x			
	2.3: Perform binary addition and subtraction by hand.			x			
	2.4: Use two's complement numbers to represent negative numbers.			x			
Module 3: To understand the basic electrical operation of digital circuits.	**3.1:** Describe the functional operation of a basic logic gate using truth tables, logic expressions, and logic waveforms.	x					
	3.2: Analyze the DC and AC behavior of a digital circuit to verify it is operating within specification.				x		
	3.3: Describe the meaning of a logic family and the operation of the most common technologies used today.	x					
	3.4: Determine the operating conditions of a logic circuit when driving various types of loads.				x		
Module 4: To understand the basic principles of combinational logic design.	**4.1:** Describe the fundamental principles and theorems of Boolean algebra.		x				
	4.2: Analyze a combinational logic circuit to determine its logic expression, truth table, and timing information.				x		
	4.3: Synthesis a logic circuit in canonical form (Sum of Products or Product of Sums) from a functional description.					x	
	4.4: Synthesize a logic circuit in minimized form (Sum of Products or Product of Sums).					x	
	4.5: Describe the causes of timing hazards in digital logic circuits and the approaches to mitigate them.		x				
Module 5: To understand the basic principles of hardware description languages.	**5.1:** Describe the role of hardware description languages in modern digital design.		x				
	5.2: Describe the fundamentals of design abstraction in modern digital design.		x				
	5.3: Describe the modern digital design flow based on hardware description languages.		x				
	5.4: Describe the fundamental constructs of VHDL.		x				
	5.5: Design a VHDL model for a combinational logic circuit using concurrent modeling techniques.					x	
	5.6: Design a VHDL model for a combinational logic circuit using a structural design approach.					x	
	5.7: Describe the role of a VHDL test bench.		x				
Module 6: To understand the basic principles of medium scale integrated circuit logic.	**6.1:** Design a decoder circuit using both the classical digital design approach and the modern HDL-based approach.				x		
	6.2: Design an encoder circuit using both the classical digital design approach and the modern HDL-based approach.				x		
	6.3: Design a multiplexer circuit using both the classical digital design approach and the modern HDL-based approach.				x		
	6.4: Design a demultiplexer circuit using both the classical digital design approach and the modern HDL-based approach.				x		
Module 7: To understand the basic operation of sequential logic circuits.	**7.1:** Describe the operation of a sequential logic storage device.		x				
	7.2: Describe sequential logic timing considerations.		x				
	7.3: Design a variety of common circuits based on sequential storage devices.					x	
	7.4: Design a finite state machine using the classical digital design approach.					x	
	7.5: Design a counter using the classical digital design approach and using an HDL-based, structural approach.					x	
	7.6: Describe the finite state machine reset condition.		x				
	7.7: Analyze a finite state machine to determine its functional operation and maximum clock frequency.				x		
Module 8: To understand the full capability of hardware description languages.	**8.1:** Describe the behavior of a VHDL process and how it is used to model sequential logic circuits.		x				
	8.2: Model combinational logic circuits using a process and conditional programming constructs.					x	
	8.3: Describe how and why signal attributes are used in VHDL models.		x				
	8.4: Design a finite state machine using the classical digital design approach.					x	
	8.5: Describe the capabilities provided by the most common VHDL packages.		x				
Module 9: To understand how hardware description languages can be used to create behavioral models of synchronous digital systems.	**9.1:** Design a VHDL behavioral model for a sequential logic storage device.					x	
	9.2: Describe the process for creating a VHDL behavioral model for a finite state machine.		x				
	9.3: Design a VHDL behavioral model for a finite state machine.					x	
	9.4: Design a VHDL behavioral model for a counter.					x	
	9.5: Design a VHDL register transfer level (RTL) model of a synchronous digital system.					x	
Module 10: To understand the basic principles of semiconductor-based memory systems.	**10.1:** Describe the basic architecture and terminology for semiconductor-based memory systems.		x				
	10.2: Describe the basic architecture of non-volatile memory systems.		x				
	10.3: Describe the basic architecture of volatile memory systems.		x				
	10.4: Design a VHDL behavioral model of a memory system.					x	
Module 11: To understand the basic principles of programmable logic	**11.1:** Describe the basic architecture and evolution of programmable logic devices.		x				
	11.2: Describe the basic architecture of Field Programmable Gate Arrays (FPGAs).		x				
Module 12: To understand the basic principles of binary arithmetic circuits.	**12.1:** Design a binary adder using both the classical digital design approach and the modern HDL-based approach.					x	
	12.2: Design a binary subtractor using both the classical digital design approach and the modern HDL-based approach.					x	
	12.3: Design a binary multiplier using both the classical digital design approach and the modern HDL-based approach.					x	
	12.4: Design a binary divider using both the classical digital design approach and the modern HDL-based approach.					x	
Module 13: To understand the basic principles of a computer system.	**13.1:** Describe the basic components and operation of computer hardware.		x				
	13.2: Describe the basic components and operation of computer software.		x				

Figure 1 Learning Outcomes in Digital Logic Developed for this Project

Also shown in figure 1 is the category of learning for each outcome. These categories come from Bloom's Taxonomy of cognition (Bloom, 1956) and represent lower vs. higher level learning. The coding of categories in figure 1 is: 1=Knowledge; 2=Comprehension; 3=Analysis; 4=Application; 5=Synthesis; and 6=Evaluation. It is important to keep in mind the learning category of each outcome when developing the assessment measures so that the tools are measuring the correct level of cognition (i.e., a synthesis outcome should have an assessment tool that measures synthesis and not a lower level category such as comprehension).

2.2 Assessment Tools

Over 600 instruments were developed to measure student performance on these outcomes. These included multiple choice questions measuring knowledge, comprehension, and analysis in addition to word problems to measure application and design problems to measure synthesis. The following figure shows an example of the types of instruments that were developed in this work.

4.3.49 For the 4-input maxterm list in Figure 4.38, give the canonical sum of products (SOP) logic expression.

$$F = \prod_{A,B,C,D}(3,7,11,15)$$

Figure 4.38

4.3.50 For the 4-input maxterm list in Figure 4.38, give the canonical sum of products (SOP) logic diagram.

4.3.51 For the 4-input maxterm list in Figure 4.38, give the minterm list.

4.3.52 For the 4-input maxterm list in Figure 4.38, give the canonical product of sums (POS) logic expression.

4.3.53 For the 4-input maxterm list in Figure 4.38, give the canonical product of sums (POS) logic diagram.

4.3.54 For the 4-input maxterm list in Figure 4.38, give the truth table.

Section 4.4 –Logic Minimization

4.4.1 For the 2-input truth table in Figure 4.39, use a K-map to derive a minimized sum of products (SOP) logic expression.

A	B	F
0	0	0
0	1	1
1	0	0
1	1	1

Figure 4.39

4.4.2 For the 2-input truth table in Figure 4.39, use a K-map to derive a minimized product of sums (POS) logic expression.

4.4.3 For the 2-input truth table in Figure 3.39, use a K-map to derive a minimized sum of products (SOP) logic expression.

1	0	0
1	1	0

Figure 4.42

4.4.8 For the 2-input truth table in Figure 4.42, use a K-map to derive a minimized product of sums (POS) logic expression.

4.4.9 For the 3-input truth table in Figure 4.43, use a K-map to derive a minimized sum of products (SOP) logic expression.

A	B	C	F
0	0	0	0
0	0	1	1
0	1	0	0
0	1	1	1
1	0	0	1
1	0	1	0
1	1	0	1
1	1	1	0

Figure 4.43

4.4.10 For the 3-input truth table in Figure 4.43, use a K-map to derive a minimized product of sums (POS) logic expression.

4.4.11 For the 3-input truth table in Figure 4.44, use a K-map to derive a minimized sum of products (SOP) logic expression.

A	B	C	F
0	0	0	0
0	0	1	0
0	1	0	1
0	1	1	0
1	0	0	1
1	0	1	0
1	1	0	1
1	1	1	0

Figure 4.44

Figure 2 Example of Assessment Measures for Digital Logic Developed in this Project

2.3 Adaptive Learning Algorithm

Once a baseline of student understanding is measured, an adaptive learning system can be put into place as a supplementary instruction component to see its impact. In this work, the level of student ability is broken down into four levels (Deficient, Basic, Proficient, and Mastery). These correlates to a typical course grading scheme of Deficient=F/D, Basic=C, Proficient=B, and Mastery=A). The objective of the adaptive learning system is to make sure each student is at a level of proficient before moving onto the graded assessment for the outcome. The entire adaptive learning system is implemented using a formative assessment strategy so that the student's grade is not effective by missing problems with the system. The following figure shows the flowchart for the adaptive learning algorithm.

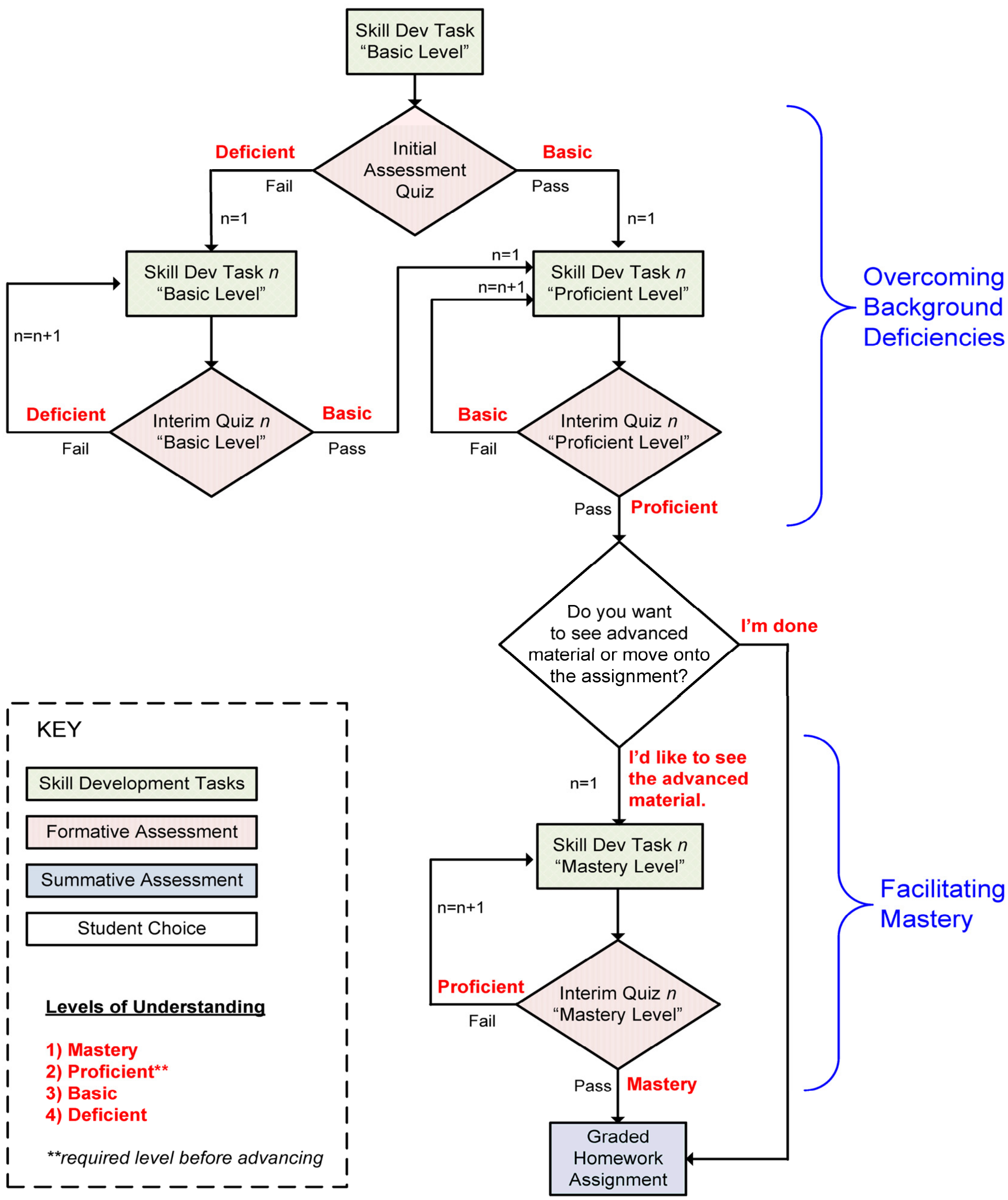

Figure 3 Adaptive Learning Algorithm Flowchart

After the student has performed all of the traditional learning activities for an outcome (i.e., reading, watching videos, viewing worked examples), an initial assessment quiz is given. The initial assessment determines whether the student is at a level of deficient or basic. Based on this assessment, skill development tasks are provided in the form of worked example videos and/or tutorials that highlight the key concepts of the outcome content. Each skill development task has the aim of preparing them to proceed to the next level by passing a subsequent assessment quiz.

Students move through the various levels (i.e., Deficient → Basic → Proficient → Mastery) by completing the skill development tasks and passing the next assessment quiz. The quizzes can be taken as many times as necessary and provide detailed feedback on each problem so that the quizzes themselves are integral to the learning. Each quiz pulls assessment tools from a test bank of questions with the appropriate level of difficulty. Students who reach the level of proficient are given the choice to proceed to the graded assignment for the outcome or participate in a Master-level skill development task. Students may opt out of the Master-level task at any time. Through continual formative assessment with detailed feedback, students are able to raise their level of understanding using this system.

2.4 Considering Student Demographics and Value Systems

One of the most key predictors of persistence is a student's experience of interest (Smith, 1999) as even highly competent students drop out of science and engineering majors citing "lack of interest" in the field (Seymour, 1997). One technique to increase interest is to use examples that the students are familiar with. This approach has shown great success in the Everyday Examples in Engineering (E^3s) program (Metz, 1999, Metz, 2011), in which problems are simply posed using material that the student body is familiar with as opposed to classical examples that don't relate to today's students. This approach doesn't change the content, or difficulty of the problem, it simply uses different examples that are more relevant to the students. As an example, consider the following example of how to calculate how long a battery will last.

Example 1. Calculating How Long a Battery Will Last	
Concept	• DC Power Consumption
Problem Statement	• A 9v battery is has a capacity of 500 mAh. If you are driving a circuit that consumes 20mW of power, how long will the battery last?

This problem is stated in the typical manner, but has little relevance to the student. A better way to pose the same problem is to use an application that the student is familiar with, such as a smart phone.

Example 2. Calculating How Long a Battery Will Last (2)	
Concept	• DC Power Consumption
Problem Statement	• Your smart phone consumes 1W of power. Its rechargeable battery has a capacity of 1000 mAh. If you charge your phone overnight and then disconnect it at 8am when you go to class, at what time will you run out of power?

Posing the problem in this way uses an example that each student is familiar with. Furthermore, this example is relevant to the students since each of them as had their phone run out of power at some point. Wording of the problem can also be used to stress other aspects of engineering, such as its contribution to public welfare and how it helps others. Consider the following example.

Example 3. Calculating How Long a Battery Will Last (3)	
Concept	• DC Power Consumption
Problem Statement	• A pacemaker consumes 1nW of power. Its battery has a capacity of 100mAh. How long will the pacemaker operate before it needs to be replaced?

This example stresses the communal value of engineering, which has been shown to be an important factor in the motivation of underrepresented groups, particularly women, to persist to graduation. Since this example may not be directly relevant to each student in the class, an adaptive system can target it toward those students with the demographics that tend to seek careers with communal value and that contribute to public welfare.

Notice that each of these three examples ask questions about the same concept. The only difference is the application that is used. The practicality of simultaneously using different forms of the same content is made possible by an adaptive e-learning system.

3. Results

3.1 Baseline Measures

Baseline data was collected at Montana State University over the course of 3 terms for the learning outcomes listed above. In order for demographic information to be collected, consent forms were signed by the students. With consent, the demographic information was pulled from university records and associated with each students' randomly assigned identification code. Figure 4 shows the students' performance on the 55 learning objectives developed in this work. At the top are the overall outcome average for the 200-level class, which covers modules 1-7, and the overall outcome average for the 300-level class, which covers modules 8-13. A vertical line is drawn at the edge of these averages to give a visual indicator of how each specific outcome score relates to the average. All scores were normalized to a 100% scale.

3.2 Pilot Study on Adaptive Learning

A small scale pilot study was conducted to see the impact of an adaptive learning module implemented for outcome 4.4 – Logic Minimization. This small scale study was implemented to verify the course management system (Desire2Learn) could implement the automatic assessment tools and competence level categorization. Figure 5 shows a snapshot of the adaptive learning environment used in the pilot study.

Of the 70 students that the adaptive learning system was offered to in the 200-level course, 60% chose to use the system. 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 results were discovered through this pilot-study. First, 16% of the students who chose to use the adaptive learning modules performed higher on the subsequent 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 and students with GPAs above 3.5 didn't see a noticeable improvement. There was an insufficient number of under-represented minorities in the pilot study to form any conclusions on the influence of gender or ethnicity. 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 desired more adaptive learning exercises.

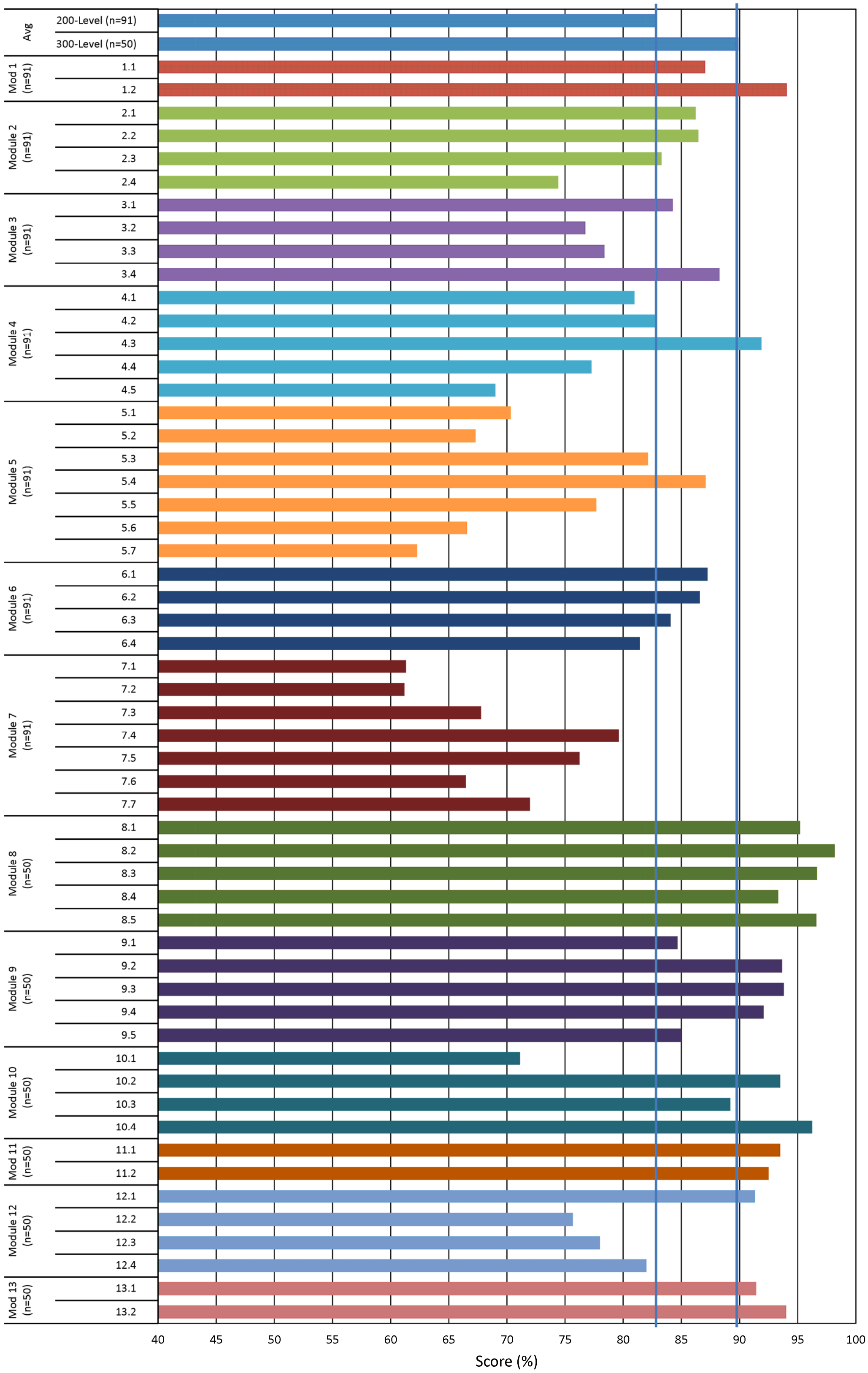

Figure 4 Baseline Understanding on the Learning Outcomes

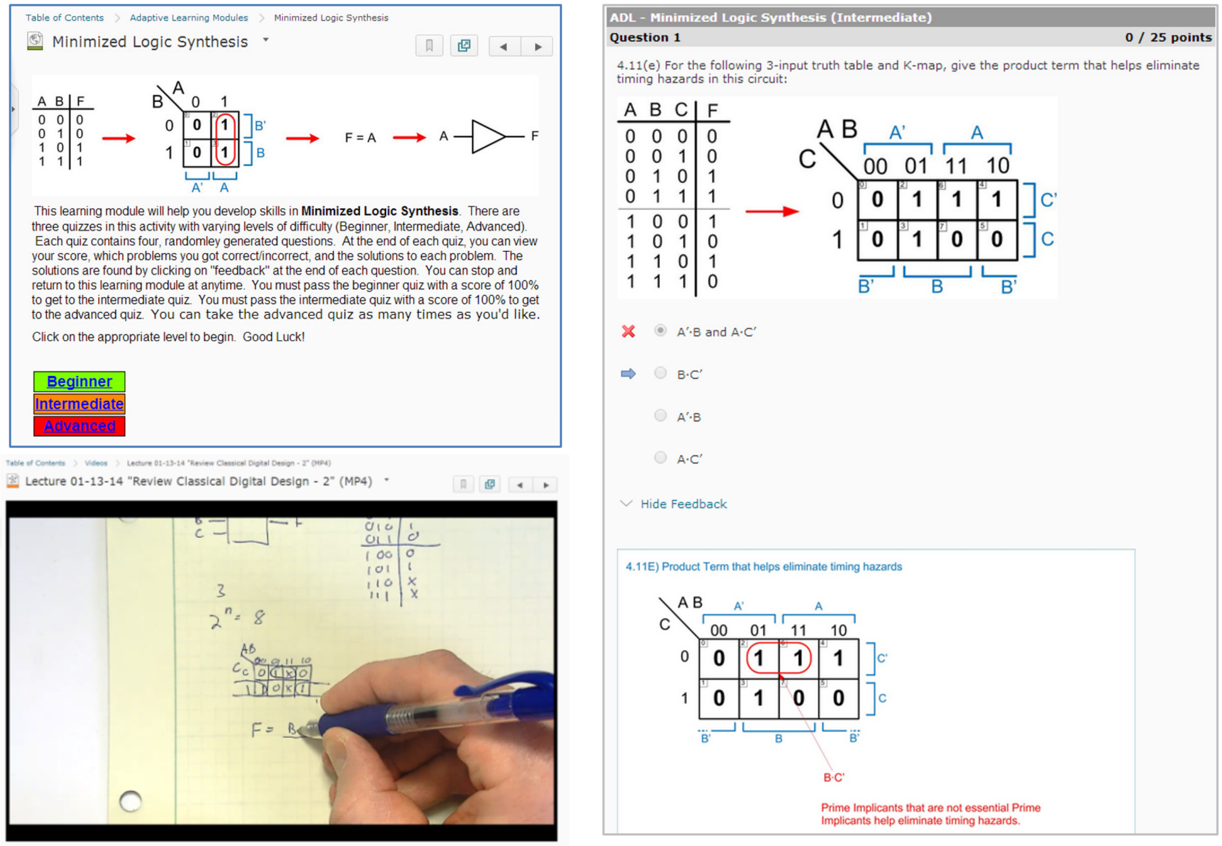

Figure 5 Snapshot of the Adaptive Learning Environment used in the Pilot Study

4. Current Status

4.1 Wide-Scale Deployment

Based on the results presented in this paper, an adaptive learning system has the ability to improve student learning and also be implemented using a standard course management system. We are currently developing adaptive learning modules for specific outcomes for deployment in the next academic term. The data collected will contain student demographics in order to determine if there are any confounding variables that highlight certain students benefit from the adaptive learning system more than others. Initial results are expected by the end of 2016.

4.2 Infusing Demo-graphic Specific Applications

Once the adaptive learning system is in place, we will be able to test interventions that change the wording and applications of the problems to target the interests of certain student demographics. Our initial focus will be improving the interest of female students. We will randomly assign the students into two groups. The first group will be the control group and will use the adaptive learning systems described in 4.1. The second group will have different applications that will highlight the communal value of the material, but will still measure performance on the learning outcome. A survey will then be administered to measure the motivation to persist in continuing in computer science and engineering is affected. Initial results are expected by the end of 2017.

5. Conclusion

This paper presented the development of an adaptive learning system that promises to address background deficiencies and facilitate mastery of introductory digital logic concepts. The system incrementally increases the level of difficulty of the learning material in order to guide the student learning. Through a continual formative assessment, students are able to improve their understanding of the material without consuming instructor time. This allows each student to reach the level of *proficient* before performing the graded assessment for each outcome. This paper presented 55 specific learning outcomes that match two courses commonly found in ABET accredited computer science and engineering curriculums. Each outcome had a corresponding learning category that mapped to a level within Bloom's Taxonomy for cognition. We presented baseline data on student understanding across these outcomes. The architecture of the adaptive learning system was presented in addition to the results of a pilot study on one outcome. The pilot study indicated that student performance on subsequent exams was improved with the largest gains being obtained by students with GPAs between 3.0 and 3.5. Our next steps include wide scale deployment and testing whether using applications of the material that have been shown to highlight the communal value of the content will improve the motivation of certain student groups, specifically underrepresented minorities and first generation college students, to persists in computer science and engineering curriculums.

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