An Intelligent Tutoring System for Logic Circuit Design Problem Solving

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ABSTRACT
As students learn about logic circuit design, they come across understanding concepts of Boolean Algebra. For some students, dealing with complex logical expressions could be a frustrating experience that may obstruct understanding as well as the development of the required design skills. Intelligent Tutoring Systems (ITS) could provide an excellent one-on-one support to improve conceptual and procedural understanding needed to overcome that problem. In addition, the use of Bayesian Networks has been found to be a reliable technique in dealing with different uncertainties encountered during student knowledge assessment. Therefore students' misunderstanding is identified as precise as possible, and hence proper feedback is provided. Correcting such misunderstanding is anticipated to improve students' overall conceptual understanding thereby leading to improving their achievement in logic design courses.

General Terms
Intelligent Tutoring Systems, Logic Circuit Design, Boolean Algebra, Bayesian Networks.

1. INTRODUCTION
Digital electronics is one of the essential courses for engineering students. As students learn about logic circuit design, they come across understanding concepts of Boolean Algebra. It is a valuable tool that enables the learner to simplify logic circuits during design as much as possible. That in turn is expected to increase the efficiency of the designed system while keeping the overall cost at minimum. For some students, dealing with complex logical expressions could be a frustrating experience that hinders the understanding and the development of the required skills. This could become problematic as course instructors introduce other topics that are related to the understanding of Boolean Algebra (e.g. using K-maps). ITS could provide an excellent one-on-one support to improve conceptual and procedural understanding of that topic. ITS has many advantages over Computer Assisted Instructions (CAI) systems, which sometimes lack the adaptability of instruction during the tutoring process as well as the precision of identification of conceptual misunderstanding. They do not consider the diversity of users' knowledge states, and as a result they do not provide flexible instructional plans that could handle such diversity [1, 2, 3, 4]. On the other hand, a few researchers developed several projects that utilize ITS in many areas. For example, some worked on improving students' understanding of mathematics in order to enhance students' achievements in high-stakes standards-based tests (K-12) [5, 6]. Others focused on assisting electrical engineering undergraduate students studying circuits' courses. Not only that, but their system situated students in a virtual environment as if they have already graduated, hired, and required to solve real life problems [7]. Another group of researchers tackled practical, real life, problems such as Auto Tutor that handled teaching driving [8] as well as training Control Center operators in tasks like incident diagnosis and service restoration of power systems [9]. However, none of the aforementioned designed systems tackle student understanding of logic design despite its importance at the undergraduate level as well as after graduation. The current proposed ITS is expected to improve student's understanding of Boolean Algebra by facilitating a one-on-one tutoring support. This tutoring is differentiated according to the student's knowledge. The designed ITS system is expected to be used in teaching university students who are studying digital electronics design. As well, several sessions of professional development workshops are expected to be facilitated for faculties who are interested in improving their students' understanding using the developed tool.
Section two gives an idea about the structure of the proposed intelligent tutoring system describing its different modules as well as the relationship among these modules. Section three focuses on the concept of Bayesian Networks starting from introducing the theory behind it to its deployment in the proposed system. The paper concludes with section four which discusses future research directions and ends with section five as the conclusion.

2. STRUCTURE OF THE PROPOSED ITS
In general, ITS comprises four subsystems: the knowledge domain, the student module, the instructional module, and the presentation module [10, 11]. Those subsystems interact in a unique way to guide the teaching and learning process (see Figure 1). A continuous and timely feedback is provided as the system assess student's learning progress. Eventually, this continuous process is expected to improve student's conceptual and procedural understanding. The knowledge domain stores the learning materials needed for students' tutoring.

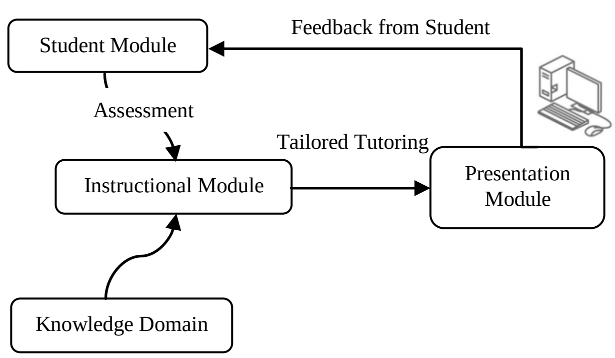

Figure 1: Structure of the proposed ITS

The ITS is expected to manipulate and reason within the knowledge represented in that domain. The student module contains the information about the student being tutored. This information could be about the student's knowledge level on the topic being taught as well as the student's learning attitudes.

The instructional module or the pedagogical module decides which teaching strategy should be used while tutoring a particular student. Therefore, it adapts itself according to the information provided by the student module. Perhaps this module is one of the main features that makes an ITS advantageous over CAI systems.

As mentioned earlier, ITS provides an adaptive instruction that changes dynamically according to the student's knowledge state during the tutoring session. The final module is the presentation module where communication between the tutoring system and the student takes place. Through that interaction the student is assessed and the assessment information is stored in the student module. Based on student assessment the instructional module decides the next step that should be presented to the student.

In this current research the user interface plays an important role of communication with the student who is using the system. The questionnaire section is separate from the feedback section. In addition, the Bayesian Networks mechanism decides which concepts are understood or misunderstood. During that process simple feedback screens cascade in a scaffolding pattern to smooth the understanding process. Overall, as students interact with the designed ITS questions, the system collects information about the level of students' understanding.

Figure 2 illustrates a sample of the questions that the student may encounter as he interacts with the proposed system. The question asks the student to choose the correct answer that represents the complement function F\` of a given function F. If the student is well acquainted with the concept behind DeMorgan's theorem, he should conclude that the value of F\` is (A+B)CDE. That in turn entails that the student understands the concepts behind logic gate functions as well as axioms of Boolean Algebra. If the student picks the wrong answer, that means he needs to review the aforementioned concepts in order to solve similar design problems in the future.

The system consults the Bayesian network to identify the most probable cause of the encountered misunderstanding. Once identified, student misunderstanding is dealt with according to the possible cause that led to it. Figure 3 illustrates the ITS feedback to the student in response to his wrong answer. The system simply responds with a primary feedback that first clarifies the correct answer and then suggests reviewing *Lecture 19* concept. Lecture 19 covers the concept of Basic of DeMorgan's theorem (See Figure 4). If the student does not understand that concept, the system suggests going back to study the functions of logic gates as well as the axioms used in dealing with logical expressions.

3. USING BAYESIAN NETWORKS

3.1 Bayes' Theorem

In Bayes theorem the probability represents a degree of belief. Initial probabilities are calculated using prior beliefs, and then new beliefs are updates as new evidences take place in the system. The prior probabilities, or beliefs, represent background information about the situation at hand. When a new evidence *e* takes place, the conditional probability $P(h|e)$ of event *h* given event *e* is the posterior probability of *h*.

The following rule governs that relation:

$$p(h|e) = p(e|h) * p(h)/p(e)$$

In a broader sense, if we consider $S = \{v_1, v_2, \ldots, v_n\}$ as a finite set of discrete random variables, we can define a joint probability distribution (JPD) as a function *p* where $0 \leq p(s) \leq 1$ and $\sum p(s)=1$. We refer to *p* as a probability distribution on *S*. Let us define X to be a finite set of variables. At that point, we can define a conditional probability distribution (CPD) for v_i given X by $p(v_i|X)$. That probability distribution also holds the following property: $\sum p(v_i|X)=1$.

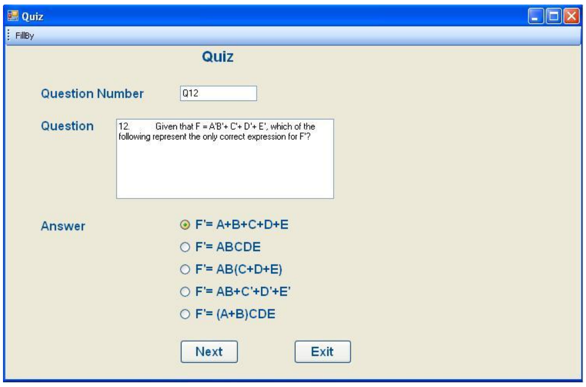

Figure 2: A sample question from student's assessment

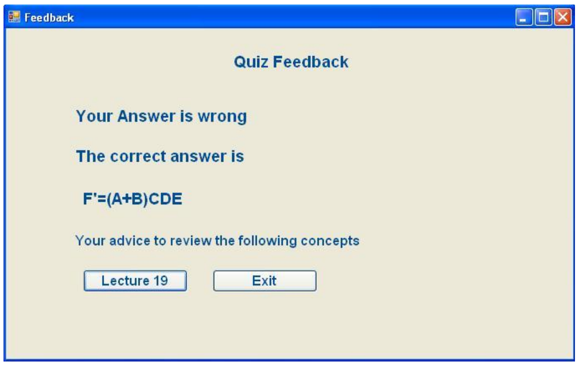

Figure 3: A sample feedback response

3.2 Bayesian Networks

Bayesian Networks can be used as a graphical representation of independent information. We can define it as a pair (D,C), where D is the Directed Acyclic Graph (DAG) on a set of binary variables, for example in this research, $U = \{a, b, c, d, e, f\}$. C, on the other hand, represents the set of conditional probability distributions: $C = \{p(v_i|P_i) \mid v_i \in D\}$, where P_i represents the parent set of each variable v_i in the DAG D (see Figure 5).

Using the concept of conditional independence we have I(f,de,abc), I(f,d,a), I(f,e,c), I(f,e,b). These independencies lead to the following conditional independencies which hold on *U*:

$$p(f|d,e,a,b,c) = p(f|d,e)$$
$$p(f|d,a) = p(f|d)$$
$$p(f|e,c) = p(f|e)$$
$$p(f|e,b) = p(f|e)$$

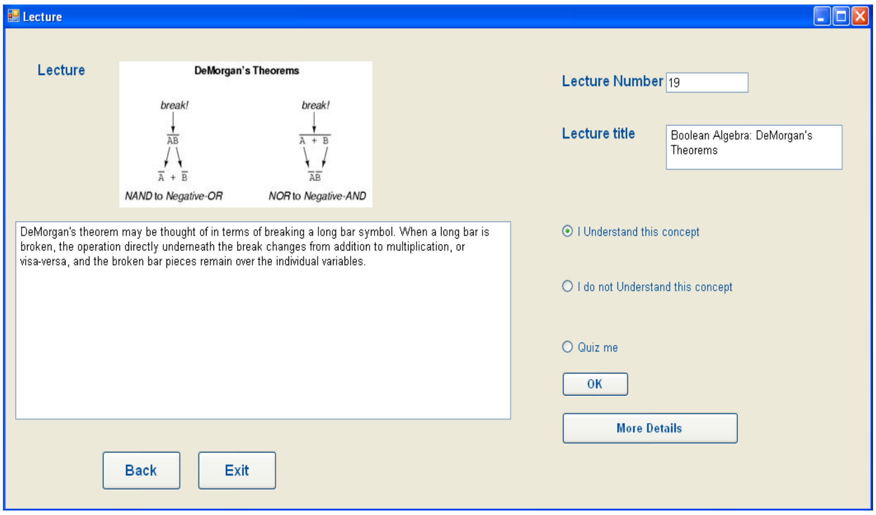

Figure 4: A sample feedback lecture to correct misunderstanding

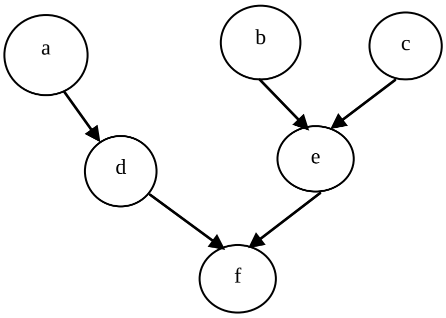

Figure 5: A directed acyclic graph (DAG) on variables *U = {a, b, c, d, e, f}*

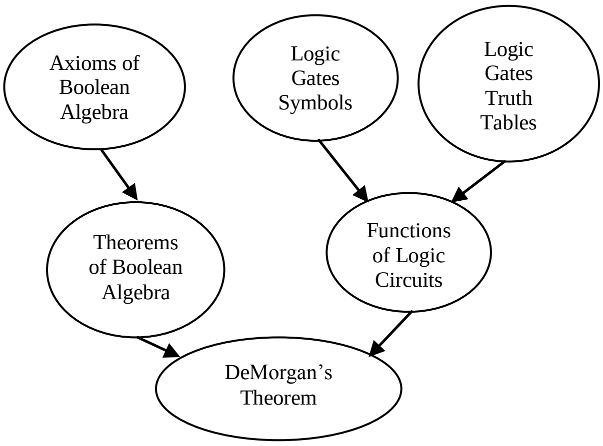

Figure 6: Modeling the prerequisite concepts required for understanding the concept of DeMorgan's theorem

The use of conditional independencies is considered useful, because it facilitates the acquisition of the JPDs. Therefore, there is no need to specify $2^n - 1$ entries for a distribution over n binary variables. That means given a set of CPDs for the variables on U, the remaining conditional probabilities can be calculated. One Bayesian Network on U is the DAG illustrated in Figure 5. Using that DAG, the proposed ITS bases its modeling of the prerequisite concepts required for solving a combinational logic design problem (see Figure 6).

3.3 The Bayesian Inference

Bayesian Networks facilitates the modeling of the structure of a problem domain [12, 13, 14]. In this research, a Bayesian inference is used to guide the tutoring process. In addition it allows tracking students' knowledge as they navigate within the problem domain. In this network, only clusters of concepts that could interact are considered and presented. Each concept within the problem domain is represented by a node in the Bayesian Network.

Boolean Algebra theorems that are used in the design process, for example, are derived from axioms such as Inverse laws, Commutative laws, and Distributive laws. Once understood, a student can deal with theories that comprise other laws such as Idempotent laws, Absorption laws, and DeMorgan's theorem [15, 16]. Figure 6 illustrates part of the Bayesian Network used in the design of the problem domain for the current proposed ITS. In that figure, a DAG is constructed to show dependencies that hold among different nodes in the graph. The DAG illustrates the proper sequence of learning for different concepts in the problem domain. For example, understanding the concept behind the axioms of Boolean Algebra is a prerequisite for understanding its theorems. As well, understanding these theorems and the functions of different logic circuits are prerequisites for understanding DeMorgan's theorem. As mentioned earlier the presented DAG is just a part of a larger DAG that encompasses logic circuit simplification using different rules of Boolean Algebra.

In the proposed design, the used CPDs for the DAG are obtained from the results of short and long formative assessment quizzes that were meant to assess students' understanding.

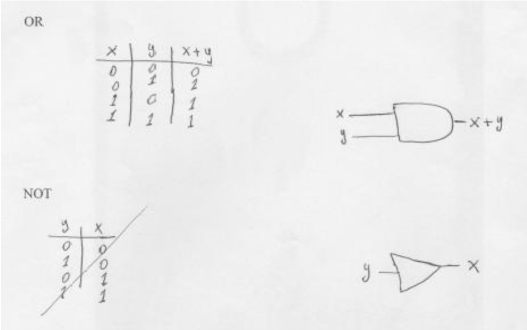

Figure 7: Answer sample of the written formative assessment questions

Figure 7 shows part of an answer sample of the assessment questions that utilizes the prerequisite concepts of "*Understanding the Functions of Logic Circuits*" construct. According to the designed Bayesian Network, the student has a misunderstanding of the truth table representation concept of the NOT gate. The student has a problem recalling the symbol of the OR gate as well, but this should not count towards conceptual understanding. To correct such truth table misunderstanding in the proposed ITS, the use of electronic circuits with mechanical switches was deployed in the feedback lectures. The use of this methodology improves students understanding instead of relying on student's memorization of the truth tables.

In general, the designed ITS quizzes included open ended questions asking students to investigate digital logic circuits as well as the logical expressions that represent these circuits. The concepts behind some of these questions tackled understanding logic gates symbols and logic gates truth tables. Other concepts tackled axioms of Boolean Algebra and focused on investigating students' ability to utilize these axioms interchangeably to minimize and compare logic circuits. If the students answer the question correctly, the concept is marked as known. In case the student answers incorrectly, then the concept was marked as unknown. However, there is a limitation to that method since the questions are open ended questions. Using this type of questions leaves the door open for some answers to be partially incorrect or partially correct. To simplify the design of the CPDs, only two states for concept understanding were experiment where students actually interact with its components. As well, statistical analysis should follow to judge the considered (See Table 1).

Logic Gates Symbols	Logic Gates Truth Tables	Functions of Logic Circuits	Corresponding CPD
Unknown	Unknown	Known	0.15
Unknown	Known	Known	0.50
Known	Unknown	Known	0.20
Known	Known	Known	0.75

Table 1. Modeling the prerequisite concepts for "*Understanding DeMorgan's Theorem"* construct

4. FUTURE DIRECTIONS

Despite the amount of effort spent on the current research to make it robust, there are few stages that should follow as future work. For example the designed ITS has to be tested using a real experiment where students actually interact with its components. As well statistical analysis should follow to judge the merit of the designed system. Before doing that, a pilot test has to take place to make sure that the assumed as well as the calculated CPDs lead to a better judgment on student's level of understanding despite the present uncertainties within the Bayesian Network. Unfortunately conducting such experiment at the mean time is a financial challenge that requires budget approval as well as other overheads. However, despite that limitation, the current designed research, in its context, is a valuable tool that could improve students' understanding.

It worth mentioning that the primary implementation of this research is in VisualBasic.NET on standalone machines. One of the future goals of the proposed research is to facilitate the use of the ITS as an e-learning tool. Therefore, suitable adjustments are planned to facilitate achieving that goal. As well, adding other design tools such as Karnaugh-maps and Quine-McCluskey methods will be taken into consideration to deal with more variables in the design process. Finally, elevating the design level to embrace sequential logic circuits is an ultimate goal that will improve the effectiveness of the proposed ITS as it guides students' learning. Again, it would be more effective if an experiment is designed to test the effect of the use of the proposed ITS on students' understanding of logic circuit design. Such experiment could be implemented on two different groups, where the control group is exposed to regular class teaching techniques. On the other hand, the experimental group is advantaged by being exposed to the proposed ITS in addition to the regular class teaching techniques. It is expected that the achievement of the later group would exceed the former.

5. CONCLUSION

The proposed project is a framework for an ITS that is anticipated to support students with diverse learning styles to understand the basics of logic circuit design. Such remedial is expected to improve students' understanding as well as to correct different misconceptions that student may have. These corrections are highly desirable especially when teachers try to build upon concepts already mastered by the ITS. In addition, while designing the proposed ITS, Bayesian Networks showed that it is a reliable technique in dealing with different uncertainties encountered during student knowledge assessment. Finally, building an ITS that deals with a learning problem during logic circuit design is a novel approach and is expected to improve the understanding of a wide range of learners leading to a development of individuals who have a solid foundation in logic design.

7. REFERENCES

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