Web-Based eTutor for Learning Electrical Circuit Analysis

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Abstract: This paper discusses a web-based eTutor for learning electrical circuit analysis. The eTutor system components, mainly the user-interface and the assessment model, are described. The system architecture developed provides a framework to support interactive sessions between the human and the machine for the case when the human is a student and the machine a tutor and also for the case when the roles of the human and the machine are swapped. To motivate the usefulness of the data gathered, some examples of interactive sessions are given and models to capture both declarative and procedural knowledge during learning are discussed. A probabilistic assessment model is reviewed and future directions in the field of eTutors for electrical circuits are discussed.

Keywords: electrical circuits, intelligent tutoring systems, web-based tutor, graphical user interface, automated assessment

Society requires knowledgeable and skilled workers and professionals. Compared to the other countries in the EU, it is evident that Malta requires more engineers. On average 2.14% of the employees in the EU work in the engineering profession in recent years, compared to only 1.06% in Malta.[1] Most industries in Malta are trying to fill up the gap left in the engineering jobs by employing foreign engineers. While this is not to be discouraged, it is a clear sign that Malta would benefit if its tertiary education system produced more

1 V. Erdmann and T. Schumann, 'European Engineering Report' (Germany, 2010).

qualified and competent engineers and technicians. For this to happen, the secondary schools that feed students to the tertiary education institutions can help by improving the way that science, technology, engineering and mathematics (STEM) subjects are taught.

It is a well-known fact in education that one-to-one tutoring helps students to improve their achievements while studying,[2] but one-to-one tutoring for all, with human tutors is not possible. Alternatively, a way to achieve such tutoring is computer-based Intelligent Tutoring Systems (ITSs) which can help the human tutors.

The architecture for a typical ITS is shown in Figure 1. The main components of such a system are a domain expert model, a student model, a pedagogical model and the human computer interface, which should not be underestimated. Additionally, the human tutor model is added to tune the ITS system to the peculiarities of specific human tutors. The way the human student interacts with the system is defined by the user interface. The interface selected has a pronounced effect on the pedagogical nature of the ITS. It can, for example, limit the types of inputs that a student is allowed to enter. In general, the ITS research community agrees that the problem-solving environment should emulate as far as possible the real world environment and at the same time facilitate the learning process,[3] even though any scaffolding should be completely removed at the tail-end of the learning process.[4] The user interface is discussed further in this paper.

2 B.S. Bloom, 'The 2 sigma problem: The search for methods of group instruction as effective as one-to-one tutoring', *Educational Researcher*, Vol. 13 (1984), 4–16.

3 A.T. Corbett, K.R. Koedinger, and J.R. Anderson, 'Intelligent tutoring systems', *Handbook of Human-Computer Interaction, Elsevier Science*, Vol. 37 (1997).

4 R.R.V.D. Stuyf, 'Scaffolding as a teaching strategy', *Adolescent Learning and Development* (2002).

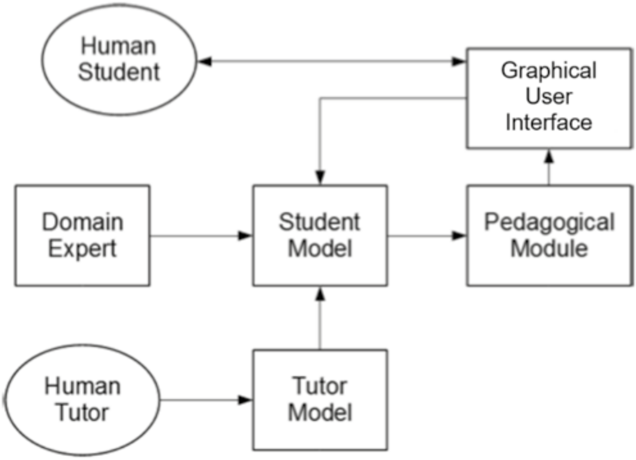

Figure 1 The architecture for the Intelligent Tutoring System, derived from Corbett [5] and Hwana [6]

The domain expert module provides an interpretation of the student's input and determines whether the assertions of the students are correct in the specific domain area. This module is therefore at the heart of any assessment system and is a benchmark that students strive to reach. The student model is a record of the knowledge state of a student. In its most simple form it is a copy of the expert's model that is tagged with information of how well the student has demonstrated knowledge of each component in the expert model. The latter is often termed 'declarative knowledge'. The pedagogical module decides the problems and sequence that are presented to the student and at which moment it offers support to the student. This model is usually considered to be domain independent. Notwithstanding the significant progress in the field of ITS, the products developed are still deemed not as effective as a human tutor in leading discussions with students.[7]

5 Corbett *et al*.

6 H.S. Hwana, 'Intelligent tutoring systems: An overview', *Artificial Intelligence Review*, Vol. 4 (1990), 251–77.

7 M. Mishra, V. Mishra, and H. Sharma, 'Intellectual ability planning for intelligent tutoring system in computer science engineering education', *Emerging Trends and Applications in Computer Science (NCETACS), 3rd National Conference on IEEE* (2012), 26–30.

This paper describes the development and study of a web-based automated tutor that helps in teaching basic electrical circuit analysis concepts. This web-based tutor helps students to analyse DC circuits made up of batteries and resistors. Furthermore it also assesses the performance of the students who use it.

User-interfaces for eTutor systems

Since the late 1980s the most popular user-interface for computers has been the windows, icons, menus, and pointer (WIMP) interface in which a mouse is used for the pointer. The WIMP interface is an effective and accurate user-interface for many different applications. In the early 1990s audio output, like sound effects and music, became common additions to the WIMP interface. Still this interface is limited in scope when compared to human-to-human interactions.

From the point of view of a student being tutored, the ideal tutor would probably be exactly like a human being, i.e. the human tutor replaced by a human-like robot, or android, which would move around the classroom with the same agility of a human and, for example, be able to sit down next to the student. However, the idea of a physical robot that is so capable and human-like is still out of reach and it will probably remain so for many more years. Still, if we let go of the idea of having a human-like robot, we can still hold on to the idea that the interactions which the automated tutor supports over a system consisting of a touch-screen, keyboard, mouse, camera, speakers, and stylus, will be as human-like as possible.

Ideally the automated tutor would listen to the user's spoken input, reply, and ask questions in audio and observe the user's hand-drawn circuit diagrams and calculations. Speech recognition and synthesis technology has now advanced to a state that can be readily integrated in an ITS system. On the other hand, prior to using the latter technology, the automated tutor itself has to produce relevant, clear, helpful, and human-like textual output. A number of automated tutors[8] and domain-

8 M. Ahmed and M.M. Bayoumi, 'An Artificial Intelligent Instructor for Electrical Circuits', *Proceedings of 37th Midwest Symposium on Circuits and Systems*, Vol. 2 (1994), 1362–65

expert systems[9] attempt to generate textual output for specific types of electrical circuits, for example simple DC electrical circuits or AC electrical circuits made up of signal generators, resistors, capacitors, and inductors. Research carried out on chatbots is related to generating text. In the last few years chatbots that make textual interactions satisfactorily human-like have been developed for a number of different domains including engineering.[10] Chatbots need to be taught the domain in which they function; in this case the domain of electrical circuits theory needs to be provided to the chatbot for it to start handling the conversation with the student. With this in place, the chatbot can ask questions about the circuit or give feedback about assertions that the student makes regarding the circuit.

Apart from textual output the presently available automated tutors make use of graphical output. Naturally they show the schematic diagram of the electrical circuit that the student wants to analyse. Some of these tutors also show arrows that indicate the directions of the currents and voltages inside the circuit. It should also be possible for these automated tutors to provide simple animations to show some of the actions happening inside a circuit, like the flow of current and the charging of a capacitor Such animations have been already used in electrical circuit simulators like Proteus Isis from Labcenter Electronics.[11]

Some eTutors have incorporated 3D Avatars in them, usually having a human form, as a front end that does empathetic gestures and facial expressions while the tutoring is taking place.[12] Another possibility that is being researched is that of using Augmented Reality. For example, J.M. Gutierreza *et al*. have used head-mounted displays (HMD) and tablet PCs to visualize the virtual objects during laboratory sessions

9 J.D. Kleer, 'How Circuits Work', *Artificial Intelligence* (Holland, 1984), 205–80

10 S. Crown, A. Fuentes, R. Jones, R. Nambiar, and D. Crown, 'Ann G. Neering: Interactive Chatbot to Motivate and Engage Engineering Students.' *Computers in Education Journal*, Vol. 2, No. 2 (2011), 24–34.

11 Proteus, 'Electronics Courses with the Proteus schematic capture program', [online] Available at: https://www.labcenter.com/education/#Electronics Courses (accessed 29 August 2017).

12 H.V. Diez, S. Garcia, J.R. Sanchez, M.D.P. Carretero, '3D Animated Agent for Tutoring Based on WebGL' *Web3D '13 Proceedings of the 18th International Conference on 3D Web Technology* (2013) 129–34.

carried out in an electric machines laboratory.[13] There are also studies of how multiple devices, for example a desktop computer and a mobile, can be used together to enhance the user experience.[14] Software Tools have been created to help in the development of these different types of user interfaces.[15]

The developed user-interface

The PHP server-side scripting language has been used to code the user-interface of the eTutor reported in this paper. PHP is purpose-built for the creation of websites, including dynamic websites, like the one developed for this eTutor. Furthermore PHP is freely available for use without any licensing costs.

Figure 2 shows a snapshot of the user interface of the web-based tutor. The input commands and the responses generated by the eTutor are shown in the upper part of the webpage. Commands are inputted to the eTutor via an HTML form while a list of the past commands is shown in a scrollable HTML text area together with the response that the eTutor gave for each command.

The circuit schematic is drawn in the lower part of the webpage. The whole webpage is scrollable, so large circuits schematics that do not fit into one screen can still be accommodated. The graphics of the components, nodes, and wires that make up the schematic of the electrical circuits are created using Scalable Vector Graphics (SVGs) which are rendered locally on the internet browser of the client PCs that the students use.

Interaction using this user-interface

Commands can be inputted to the eTutor one at a time with the eTutor giving a response as soon a command is entered. The circuit can be built by inserting commands into the eTutor. Examples of tasks that can be

13 J.M. Gutierrez, E. Guinters, and D.P. Lopez, 'Improving strategy of self-learning in engineering: laboratories with augmented reality', *Procedia – Social and Behavioral Sciences*, Vol. 51 (2012), 832–9.

14 F. Paterino, 'User Interface Design Adaptation', *The Encyclopedia of Human-Computer Interaction*, 2nd ed. (2014) 39.

15 B. Myers, S.E. Hudson, and R. Pausch, 'Past, Present, and Future of User Interface Software Tools', *Carnegie Mellon University, ACM Transactions on Computer-Human Interaction (TOCHI) – Special issue on human-computer interaction in the new millennium*, Vol. 7 Issue 1 (2000), 3–28.

done to build the circuit are:

- Insertions of new nodes and components;
- Movements of nodes and components;
- Connections of components to nodes;
- Rotation of components.

The electric circuit shown in Figure 2 shows one battery and 14 resistors with resistors R9, R14, R15, and R16 being connected in parallel. An example of a statement or assertion that the user can make for this circuit is:

are_parallel R9 R14

With this assertion the user is stating that resistors R9 and R14 are connected in parallel. The reply from the tutor is:

Yes, those resistors are in parallel. Well done!

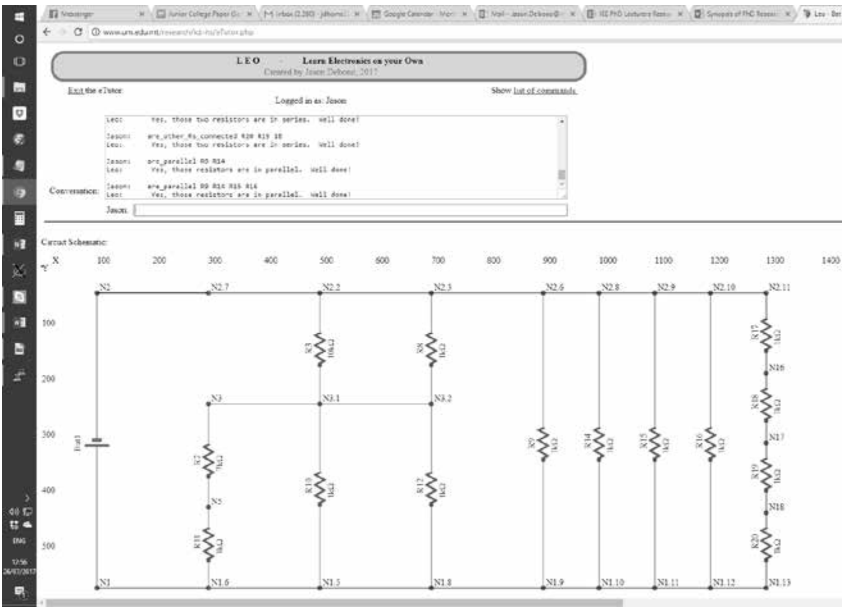

Figure 2 The user interface of the developed web-based eTutor

Assessing the knowledge learnt

The educational literature explores many different ways to assess students' work. This paper limits itself to summative/formative and declarative/procedural assessments. Examinations are summative assessments because they try to assess all the knowledge and/or skill of the student in one, usually time-constrained, assessment session. In contrast, formative assessment is done in a number of sessions, spread out during the academic year or semester in which a particular subject is being delivered. The results of one formative assessment can influence the way in which a subject is delivered following that particular formative assessment session. On the other hand, summative assessments are only meant to give a snapshot of the students' ability at a certain point in time, usually at the end of the delivery of the course. An automated tutor empowers the student to get formative assessment because the student can get frequent and immediate feedback for the work inputted with the feedback being used to improve knowledge and skills.

Knowledge can be classified into two classes: declarative and procedural,[16] hence the need for both declarative and procedural assessments. In the former the student is assessed from the statements given, which frequently are remembered facts, rules, and relationships. Procedural assessments, on the other hand, focus on the student's ability to perform a practical task and also on the problem-solving approach used. Procedural knowledge is typically ill-defined; consequently procedural assessments often involve the student having to actually perform a practical task. On the other hand, it is still common to find procedural assessments done without involving practical tasks by, for example, using written questions designed to target the knowledge of how the concerned task should be performed.

For the case of declarative knowledge statistical models may suffice, while for procedural knowledge models that consider the sequence and order, in which declarative knowledge is applied, are desired. In the electrical circuits ITSs described by Ahmed[17] and Yoshikawa[18] the

16 Corbett *et al.*

17 Ahmed *et al.*

18 A. Yoshikawa, M. Shintani, and Y. Ohba, 'Intelligent tutoring system for electric circuit exercising,' *IEEE Transactions on Education*, Vol. 35, No. 3 (1992) 222–5.

student model is limited to recording declarative knowledge while Mishra *et al*. point out that the model should also capture the knowledge flow.[19] Finally, the student model is used to assess the progress of the student and its output is very useful for the pedagogical module that observes the student and controls the actions taken by the ITS.

The developed assessment model

When the assertion 'are_parallel R9 R14', is inputted, the eTutor first logs the assertion, then uses its domain knowledge to check if resistors R9 and R14 are truly connected in parallel and finally it replies whether this statement is true or not. This is an example of a declarative assessment.

Similarly the user could check if resistors R14 and R15 in Figure 2 are in parallel or not. The tutor again logs this, checks it, confirms that this is indeed the case for the circuit in question and congratulates the user. In other words, the tutor will assess this second declaration, hence carrying declarative assessment as in the previous case.

However, if the student is more careful, or more proficient in his analysis, he will realize that R9, R14, R15, and R16 are all connected in parallel. Hence there is not really the need to check parallel connections for separate pairs of these resistors; instead the student can assert that these four resistors are connected in parallel in just one step by inputting the assertion below:

are_parallel R9 R14 R15 R16

While the automated tutor carries out a declarative check for this assertion, implicitly it also carries out a procedural assessment in that the procedure that the student used this time is faster or more efficient than that of using multiple statements in which only pairs of resistors are considered.

The same reasoning applies when assessing what the user goes through to find out which resistors are connected in series. More complex examples can be created when considering the multiple steps that the user follows to analyse a whole circuit. Most circuits will need more than one parallel or series resistor assertions. After each assertion

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new equivalent resistors replace the old sub-circuit and as a result the circuit topology changes. These iterative assertions last till there are no more parallel and series combinations. An example of this process is shown in Figure 3. The way that the student handles the whole process is used by the developed eTutor for procedural assessment.

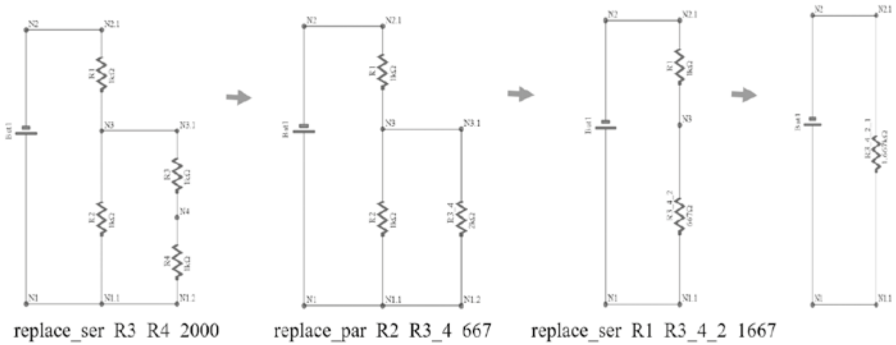

Figure 3 Examples of possible steps that the student can use to analyse a circuit

In the earlier work we used the Markovian model shown in Figure 4 to assess a class of 27 students for the analysis that they did on an electrical circuit.[20]

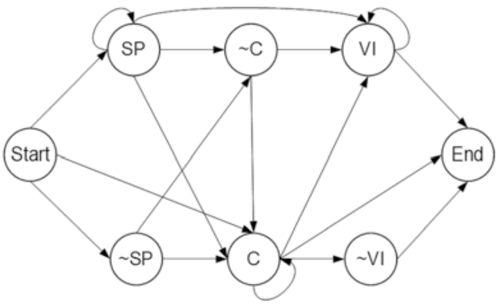

Figure 4 The Markovian model. (Not all possible transitions are shown.)

20 A. Muscat and J. Debono, 'Assessment Models and Qualitative and Symbolic Analysis Techniques for an Electrical Circuits eTutor', *International Journal on Advances in Intelligent Systems*, Vol. 5 Nos. 3 & 4 (2012), 278–90.

The students were classified into four different levels: Level 1 meaning that the students have mastered electrical circuit theory; Level 2 meaning that they did well in it; Level 3 meaning that they did poorly in it; while Level 4 meaning that they failed in learning electrical circuit theory. Four Markov models were used, one for each level. Figure 5 depicts how this classification was done.

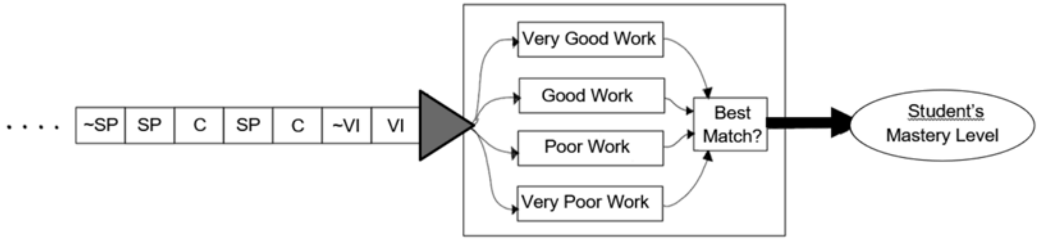

Figure 5 Likelihoods for four Markovian models are found while observing the student's steps

The students' work was assessed by one of the authors and his assessment was used to train the Markov model. When eight of the manually assessed students' works were used for training the correct classification rate was 70%, while when all the 27 works were used the correct classification rate was 93%.[21]

Future directions

This section discusses the limitations of the current system and future directions in the area of ITS for electrical circuits.

User interface design and usability study: The main advantage of the current user interface is robustness and its behaviour can be modelled as a noiseless channel, i.e. the computer stores what the user intended as input. However, this system does not resemble the natural environment in which students normally study, i.e. pen and paper on which circuits and calculations are carried out. Indeed studies in a college-level algebra class have indicated that handwriting mathematical equations

21 Muscat *et al.*

enhances the student learning experience.[22] However, the output from a computer vision (CV) based system will undoubtedly be noisy. We therefore propose the use of a limited CV system that acts as a 'rough or scribbling paper' and simply adds extra information to the procedural attentive module. The student will still use the keyboard and mouse system to enter final textual answers and circuits.

The use of Natural Language Processing (NLP) for user-machine communications: In the current system the student is required to learn the commands to successfully communicate with the eTutor. This system of communications is completely unnatural in addition to introducing an extra hurdle to the student. The obvious solution is to integrate NLP technology not only to improve the human-machine interface but also to facilitate machine learning from an appropriate corpus of electrical circuit textbooks. In this respect it may be advantageous to make use of *chatbot* technology as in the experiments reviewed above.

Use of machine learning for the eTutor to learn the domain knowledge, that is electrical circuits analysis: In the current system the domain knowledge is hard-coded. As discussed by Muscat[23] most of the computational methods to solve electrical circuits are not suitable for an eTutor since it is either not possible to trace the steps in analysis or the method itself has no resemblance to methods learnt in class. It follows that the suitable methods are those that rely on the application of a sequence of rules that are defined separately. The latter approach requires reasoning which has so far been hard-coded into the software. The challenge is to let the machine learn the atomic rules and reasoning that connects the rules together in context. This is in contrast to the current trend in visual question answering systems.[24] These systems learn how to answer questions by correlating questions to answers and it is still unknown whether such systems can learn the atomic rules in circuit analysis, which are needed for a system that answers questions through reasoning and understanding. It is therefore important to find a representation of circuits and associated descriptions that enable the explicit learning of the atomic rules.

22 L. Anthony, J. Yang, K.R. Koedinger, 'A paradigm for handwriting-based intelligent tutors', *International Journal Human-Computer Studies*, 70 (2012), 866–87.

23 Muscat *et al.*

24 S. Antol, A. Agrawal, J. Lu, M. Mitchell, D. Batra, C. L. Zitnick and D. Parikh, 'VQA: Visual Question Answering', *International Conference on Computer Vision*, (2015) 2425-2433

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