E-LEARNING SUPPORT FOR STUDENT'S UNDERSTANDING OF ELECTRONICS

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Abstract

To enhance active learning and understanding of analogue and digital electronics the use of e-learning techniques will be investigated. In a redesigned course combining introductory analogue and digital electronics, students will be motivated to prepare for lectures and exercises by providing access to interactive simulations. Some exercises will furthermore be carried out first as simulations of electrical circuits and then with physical components, i.e. as design-build exercises. A number of didactic problems in learning electricity and electronics are discussed.

Keywords: CDIO, e-learning dimensions, learning electronics, circuit simulations, didactics of engineering education

1. Background and motivation

The potential of "e-learning" techniques (such as web-based learning and instruction, interactive visualizations and simulations, and online conceptual tests) for enhancing active learning and understanding in engineering education have so far *not* been a key issue in CDIO. Although *active learning* and the *constructive alignment* of teaching and learning activities with the intended learning outcomes and their assessment are part of the CDIO standards (standard 8: active learning), the relevance of e-learning for supporting these educational goals is not considered as a systematic part of the CDIO framework [4]. Perhaps this is because it is overshadowed by the focus of CDIO on the importance of hands-on and design-build experiences. The importance of *experiential learning* through physical constructions does however *not* exclude the importance of using e-learning techniques to enhance active learning and to motivate students to prepare for lectures and exercises in the first place. In some modern branches of engineering like information technology and software engineering the domain of modeling and experimentation is already heavily exploiting virtual constructions, and this is a further argument for introducing e-learning techniques such as simulations and interactive visualizations where students can build virtual constructions. This does of cause not imply that courses in digital electronics should avoid hands-on experiences with physical constructions (e.g. of electrical circuits) as well.

2. The involved courses

The introduction of e-learning elements in the introductory courses *Electronics* and *Digital Systems* is one of many elements in a new CDIO-based study plan for the B.Eng. study in IT, which is part of the effort of DTU for introducing CDIO as the basis of all its B.Eng. studies [15]. Figure 1 below shows the courses involved in the reorganization within electronics and embedded systems in the existing (left) and in the new (right) study plan. The main CDIO-projects on the 1st and 2nd semesters are related to courses on programming and software engineering which are not addressed in this paper.

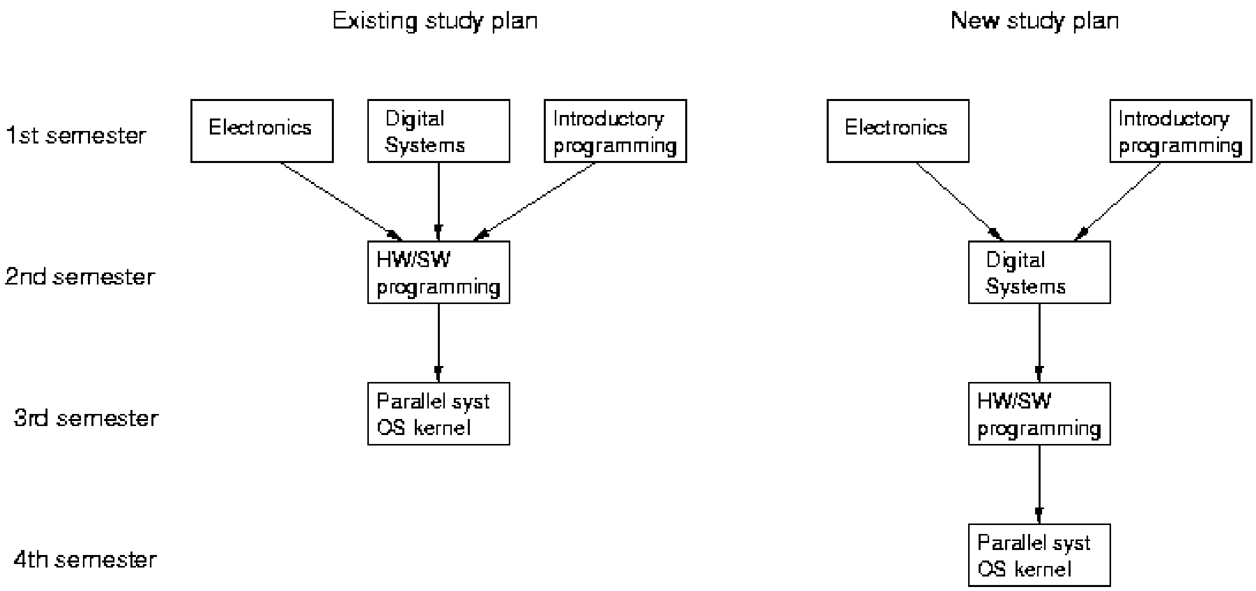

Figure 1: Reorganized part of the study plan for the B.Eng. study in IT

The course in digital systems teaches (1) design of combinatorial and sequential circuits and (2) their implementation using FPGA technology (Field-Programmable Gate Arrays) and synthesis from descriptions in the VHDL (hardware description) language. The VHDL language, the associated synthesis tool and the FPGA implementation platform are all quite complex, and *although only the simpler features are used, the complexity tend to distract the focus from the fundamental concepts*. Moreover, students are working with abstract program models of gates and wires and they are learning a hardware description language at the same time as they are learning their first software programming language. Students will therefore sometimes be confused about the role of *hardware description languages* like VHDL as opposed to *software programming languages* like e.g. Java.

In the new study plan the course Digital Systems is placed on the second semester which means that it can now benefit from prerequisites from electronics and introductory programming. Students have seen electronic components and learned a programming language, and VHDL can be introduced as just another language targeting hardware design. At the same time our aim is to introduce some very simple CDIO-like problems, i.e. problems reflecting the life-cycle of conceive-design-implement-operate, in the *Electronics* and *Digital Systems* courses, where students will:

1. Design circuits using paper and pencil (i.e. traditional problem solving).
2. Subsequently "prototype" the circuits using simple graphical tools for drawing and simulating schematics.
3. Build (some of) the actual circuits using breadboards and real components and wires.

This will be introduced in the new electronics course and continued in Digital Systems. In the future we will therefore be introducing CDIO concepts early and we will provide *visualizations of virtual constructions* (i.e. simulations) *as well as hands on experience* before introducing the more complex and abstract tools used for describing, synthesizing and prototyping digital circuits. In this way we also adapt to the observation that engineering students (as indeed all students) are "constructive learners", and that *most students today have little experience building electrical and electronic circuits* before they start. Let us first look take a look at a use scenario for student learning of analogue electronics using *5Spice*.

3. Educational scenario using 5Spice (Case 1)

5Spice is a light version of the professional electronics software *PSpice*. Although the light version have not yet found the same widespread use as the professional version, it has been used for instance to generate the schematic diagrams used as a first step towards more advanced CAD-like constructions for VLSI microelectronic circuits [18]. *5Spice* is not open source, but it can be used freely for educational purposes [23]. It is mainly used to simulate analogue electrical circuits. In the example (figure 2) a passive RC-circuit have been built in order to illustrate how the voltage builds up during the charging of a capacitor (C1).

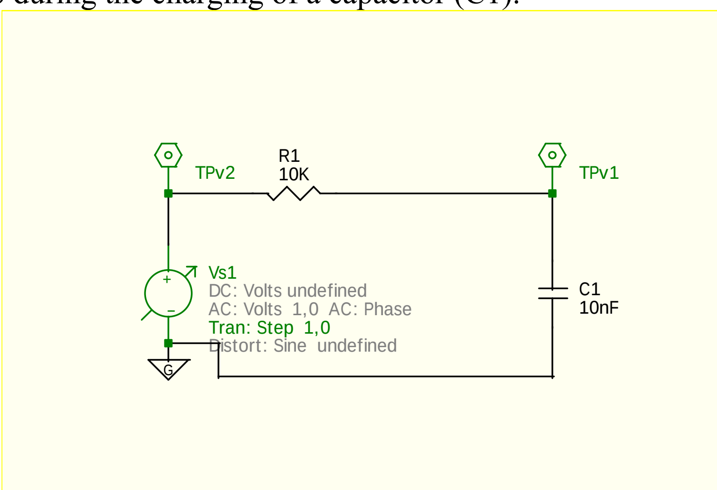

Figure 2: A simple RC-circuit constructed in 5Spice.

The behavior of the capacitor can be studied through a transient analysis of the circuit as shown in the graph of the voltage (measured with TPv1) as a function of time. After some time the voltage level reaches the voltage over the source (measured with TPv2). The graph (figure 3) demonstrates the importance of the temporal factor in electronics, since it takes several times the circuit-specific time constant ($\tau = RC$), for the capacitor to be fully charged. This delay is in principle responsible for the constraint imposed on the possible speed of computer chips, i.e. the clock frequency.

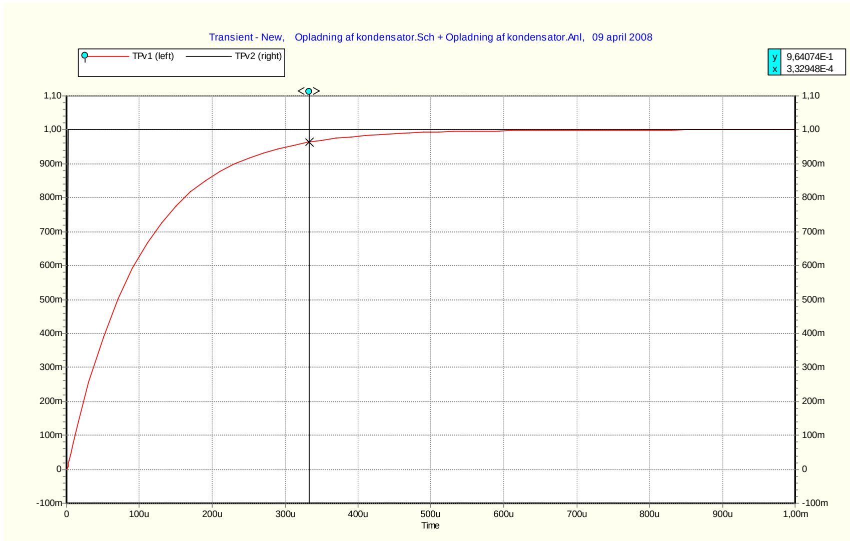

Figure 3: Graph of voltage as a function of time over the capacitor.

The example is therefore chosen for didactic reasons, because the same delay problem characterizes the RC-switch model of CMOS circuits that are used in digital circuits and microprocessors. These circuits are introduced in the new electronics course and the example (i.e. the problem of the time delay) can be used to link to two major branches of electronics within the 1. semester course, i.e. analogue and digital electronics. Figure 4 shows a PowerPoint slide from an introduction to digital electronics illustrating this fundamental problem.

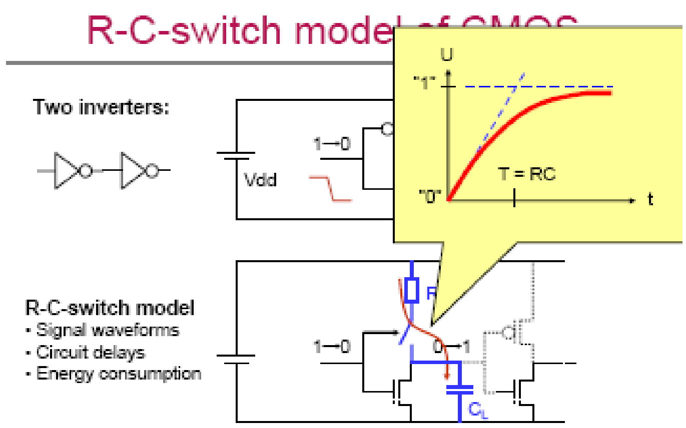

Figure 4: PowerPoint slide from an introduction to digital electronics (see text).

By using 5Spice students are given an opportunity to *construct and simulate the behavior of a circuit* which they will later *build physically in the laboratory*. The instruction for an exercise in 5Spice could be:

> "Build a virtual circuit in 5Spcie that can be used to simulate the charging of a capacitor through a resistance. Measure the voltage over the capacitor as a function of time. Let the resistance R = 10kΩ and the capacitance C=10µF, and examine through a transient analysis at which point in time the voltage over the capacitor have reached a level corresponding to 95% of its final value. "

In the graph produced by 5Spice (figure 3), the requested time can be read off the graph by using a trace represented by a vertical line intersecting the graph. The small box in the upper right corner shows the coordinates of the intersection point. In continuation of this small exercise students should also be asked to compute the time analytically and they will later be given the opportunity to build the circuit in the laboratory and examine the physical signal with an oscilloscope.

Simple simulations of this kind can also be used in the context of home work with computational exercises (without any experimental work) in order to enhance understanding of the theory as described in the textbooks for the course [9, 20], i.e. the basic physical laws of electricity (e.g. Ohm's law) and electrical circuits (e.g. Kirchhoff's laws). It is expected that student learning of these laws will be improved as well as more fun through this type of homework (or alternatively group work on campus), i.e. through the *opportunity to examine the behavior of virtual circuits and the properties of their components* (such as the capacitor in our example).

Students will gradually build up *mental models of electrical components and their behavior* within different types of circuits, if they are *exposed to many examples* and forced to *consider their variation* and the *functional roles* of different components in electrical circuits. Virtual circuits and software programs like *5Spice* are well suited for this purpose, because they support systematic variation of components and their properties and thus can be used as a kind of externally supported "thought experiments" (or what has been called "diagrammatic reasoning" in semiotics).

5Spice could also be used for more *open ended exercises* in order to train students in the *selection of relevant components* and *estimation of appropriate sizing* (of resistance, capacitance, current etc.). In the laboratory students will sometimes overload components and build circuits that will not work because of improper selection of components and sizing of properties. This also constitutes a learning experience. Virtual as well as laboratory exercises is a way to compensate for the lack of experience in modern students with "tearing things apart" and "tinkering" with mechanical and electronic devices.

4. Didactic problems of learning electricity and electronics

There are relevant didactic considerations to be made in the context of learning basic high school electricity and within introductory engineering courses in electronics. A number of studies have shown systematic problems in students understanding of the basic concepts of electricity, and we should expect these to carry over into the field of analogue electronics, e.g. from high-school physics to introductory courses in electronics. A number of key problems are mentioned below.

4.1 Problems of conceptual transfer

There is a *conceptual transfer problem* in *utilizing the mathematical requirements* when it comes to new application domains for using mathematics in physics, i.e. in describing the physics of electronic circuits through mathematical expressions [21]. Similarly there are problems of conceptual transfer in *utilizing knowledge obtained in basic electricity* in higher courses on electronics. The same phenomena are known in other domains, e.g. utilizing the vector calculus learnt in fundamental mathematics courses when in reappears in electromagnetic field theory. A special version of the problem of conceptual transfer is the problem that students encounter in higher education, when they have to recognize knowledge they already have, but in different contexts where it reappears "disguised" with slightly different perspectives and vocabulary. An example is provided by the three different versions of *thermodynamics* in higher education, i.e. as taught in *physics*, in *chemistry* and in *engineering* (e.g. in courses on energy systems) [2].

4.2 Dissociation of computational skills from comprehension

There can in general be a *dissociation problem* between the *declarative knowledge* that students might have about e.g. laws (like Ohm's law or Kirchhoff's laws) and their *ability to perform calculations and inferences*. In particular it is possible to have a basic level understanding (as a declarative knowledge) without possessing the corresponding procedural ability and vice versa. The reverse problem is well known in engineering education, i.e. the demonstration of computational skills detached from conceptual understanding [12]. In electronics students develop a skill in solving standard problems of electrical circuits through algebraic manipulation, but without considering the functional relations of the circuits. They can solve equations given a set of values, but can not always explain the properties and behavior of electrical circuits in a qualitative manner [8; 19]. Traditional computationally oriented assessments in engineering education do therefore not test student understanding. A further consequence (relevant for CDIO) is that Blooms linear taxonomy of levels of learning (where "application" in the form of e.g. computations is seen as more advanced than basic level "comprehension") needs to be revised [15].

4.3 Confusion of cause and effect

In learning about electricity there is a tendency for students to confuse cause and effect in so far as they focus on *current* rather than on *voltage* [3; 8]. This problem has also been described as the "battery-centered" model of electricity, since batteries are often seen as the sole sources and sole agents of flows in the circuits [16]. In some ways this problem can unfortunately by worsened by the motivated use of *analogies* that is supposed to enhance mental models of electrical flow by analogy to fluid flow [7]. These "water models" of electricity however give rise to misconceptions about electricity and they tend to focus students on localized events at the expense of global properties of electrical circuits and simultaneous events.

4.4 Localized versus global focus

There are two interrelated problems with regard to the mental models of electricity. On one hand students have problems with considering *simultaneous changes in several variables*, and on the other hand they have problems with the *visualization of phenomena related to electricity* as opposed to e.g. macroscopic mechanical phenomena. The latter problem is not just a problem of "visualization" in a narrow sense, but a problem of *conceptualization* of a link between *observed global effects* and the *hidden microscopic processes* that students get access to via theoretical models, e.g. movement of electrons [19]. The point of introducing these didactic problems of learning electricity is that they make it possible to *give specific reasons for the relevance of different kinds of e-learning*, since each problem need specific forms of *cognitive support.* This will be explained briefly below. Cognitive support in software engineering is discussed in [22].

5. Dimensions of e-learning support

In preparing for the introduction of e-learning tools to support student learning in introductory electronics, we have investigated a number of software tools. One option is to use java-based open source software for giving web-based instructions and quizzes to support student's homework, and as variation and visualization tool for classroom teaching. In some cases java based programs can be embedded in e-learning platforms such as Moodle [24]. E-learning platforms will also support the creation of chat rooms and other interactive facilities that students can use to cooperate on campus or from home. Another option is to instruct students to download small programs that can be freely used for educations purposes (such as *5Spice* mentioned above) for building and simulating electronic circuits. These facilities are intended to *motivate students to engage in home work* and *enhance active learning of the content.*

For considering the potential usefulness of e-learning it is however necessary to understand its "support dimensions" in an analytical sense. The problem is that different types of *cognitive support* for learning that might be provided by "e-learning" is often confused, because "e-leaning" is an ambiguous term, that does not spell out exactly what aspects of information and communication technology (ICT) is being used by the "e" in e-learning or exactly what didactic or pedagogical problems are being addressed. To give just one example of this confusion [1], it is quite common in engineering education to refer to the relevance of "multimedia" learning, although the systems being described are in fact based on *multiple representational forms* (texts, graphs, diagrams etc.) and not at all on the combination of media channels known as multimedia (audio-visual media etc.). To help remedy this confusion we should attempt to analytically distinguish *different didactic aspects* or "dimensions" of e-learning such as:

1. *The role of (static) visualization versus animation*
2. *The role of 2-D graphics versus 3D graphics*
3. *The role of (user controlled) interaction versus (model based) simulation*
4. *The role of multimedia (e.g. audio-visual media) versus multiple representational forms.*
5. *The role of linear versus hypermedia organization*

These distinctions can then be used to explore the arguments for the effects of different e-learning techniques as well as their associated *benefits and challenges* – as it is known from the methodology of *usability claims* in Human-Computer Interaction research [17]. This exploration is out of the scope of this paper, but *it can be used heuristically to set up links between different didactic problems of learning electricity and electronics and the relevant dimensions of e-learning*. As an example take the problem of considering *simultaneous changes in several variables* that we mentioned above. This is a didactic problem that can be heuristically linked to the e-learning technique of *animation*, since animation gives support for inspecting and considering *simultaneous events.* This is however not without its own didactic problems. If the simulated systems are complex as in the case of e.g. weather systems [11], animations (e.g. meteorological animations) become difficult to inspect visually, because of the many simultaneous events. In cases like these and including complex electrical circuits, students need added graphical support to *focus sequentially on different parts of the system*.

Another example is the need to visualize and construct mental models for the relations between the macroscopic level of observations (e.g. voltage measurements) and the microscopic level of physical models (e.g. interaction between electrons and the electromagnetic field). Here the cognitive support needed is not just visualizations as such, e.g. the traditional static visualizations of circuits found in textbooks, but rather the opportunity to explore what happens in different circuits under different circumstances. Students need to discover these relations on their own in order to construct relevant mental models and this can be supported by parameter variation (corresponding to though experiments, "what happens if …") with *interactive visualizations*, i.e. with simulations that provide students with the opportunity to build their own circuits.

6. Use of simple java applets versus advanced circuit simulators (Case 2)

Given the dimensions of e-learning support and the didactic problems they should address we can now better evaluate the different software tools that could be used for teaching and learning in introductory electronics. A nice example is shown below using the *Circuit Simulator* java applet [25]. It can also be used from the Moodle site of the DTU Informatics CDIO project [29].

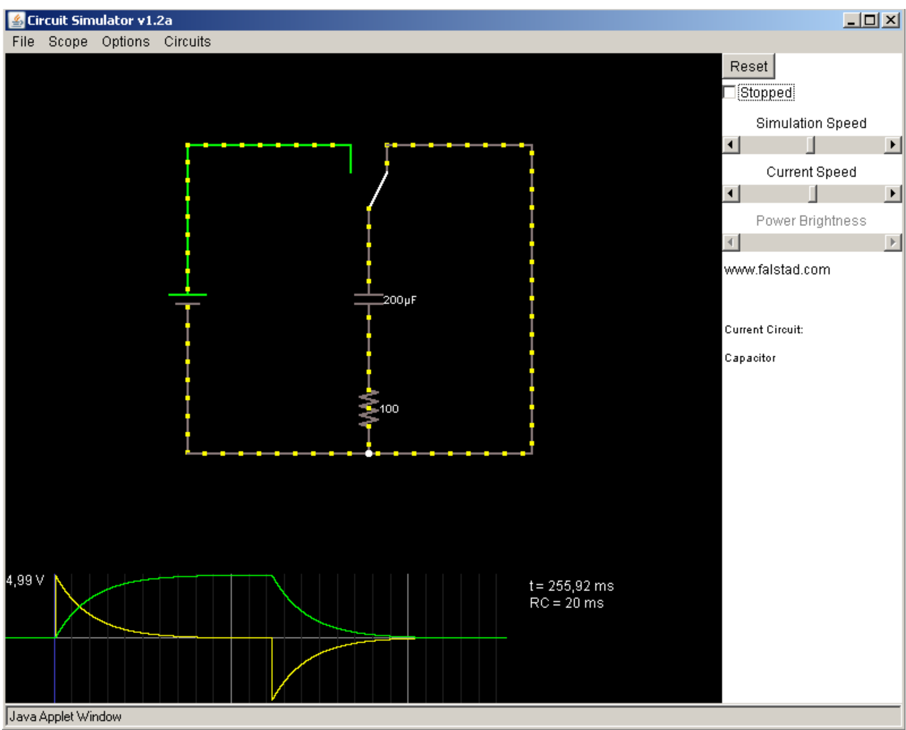

Figure 5: Java applet simulating a simple RC circuit.

The RC-circuit example can be used interactively to visualize the charging of the capacitor as well as its discharge (by clicking on the switch). Below the animated circuit (notice the representative "electrons" on the circuit) graphs are shown for the current (yellow line) and the voltage (green line) for the charging and the subsequent discharging of the capacitor. Many other preconfigured circuits of analogue and digital electronics can be chosen from the applet menu. The value of these visualizations are mainly the repetition of different circuit types that have been covered in lectures and textbooks, as well as the added value of being able to control the repetition of demonstrations, the speed of the simulation (i.e. the animation can be slowed down) and the inspection of the simultaneous graphs for current and voltage that are animated below the circuit animation. The possibility to build your own circuits is however very limited in this type of applet. The interaction is limited to selection of circuit type and a few external parameter settings (such as simulation speed and graph display selection).

This means that a tool like this could be used as *animation support for inspecting simultaneous variables like current and voltage in predefined circuits* (as discussed above), but it does not give support for the thought experiments and diagrammatic reasoning needed to construct mental models on a more advanced level of learning, i.e. the conceptual understanding of the link between the macroscopic phenomena and the microscopic models. For this *students will have to build their own circuits and discover their own mistakes and false assumptions* when experimenting with their own constructions. This kind of support can be found in more advanced tools like *Logisim* [26] and *Circuit Sandbox* [27] as well as the previously mentioned *5Spice*[23]. Below is shown an example 4-bit adder-subtractor used to control a digital numeric display.

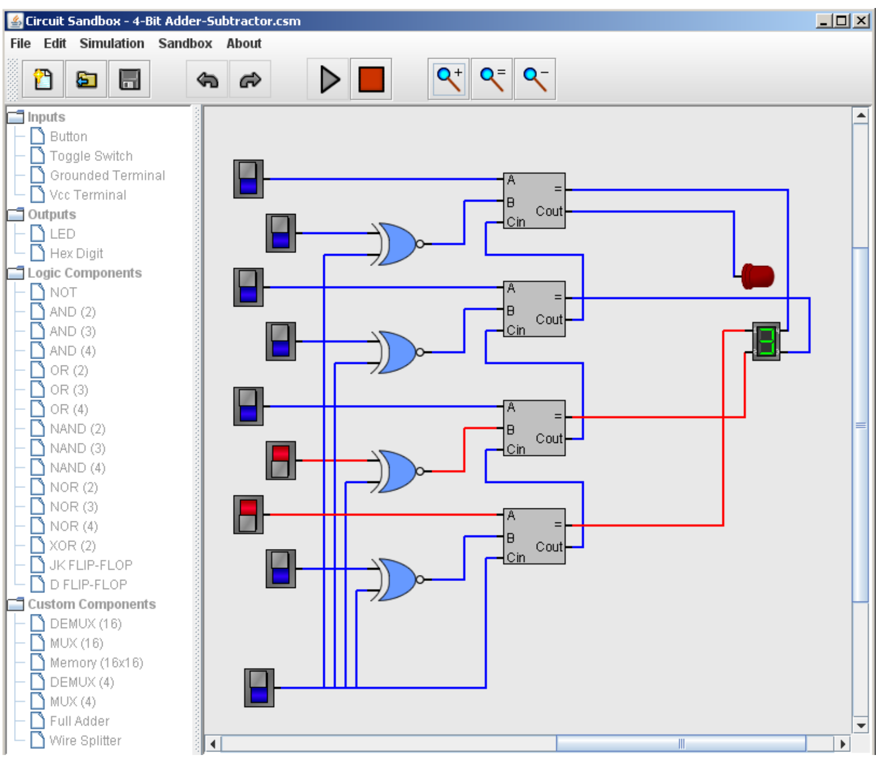

Figure 6: A 4-bit adder-subtractor for a digital numeric display in *Circuit Sandbox*

In the more advanced tools it will still be possible to try out preconfigured models, but students can also construct circuits from individual components and then run them as simulations. Some of these open source programs are java based and could be implemented as web-based simulations whereas other require students to download software to a local pc. The adder-subtractor example will be a good example of an exercise in digital electronics, where students themselves should build the circuit and its corresponding truth table.

With regard to the other dimensions of e-learning mentioned above we will just comment on the issue of 2D versus 3D graphics. It has been suggested that since there are many simultaneous variables (voltage, current, power etc.) that are usually displayed as *multiple graphs external to the diagrammatic representation of the circuit*, a possible improvement in visualization could be to integrate graphs and diagrams to obtain a 3D graph where the global relations can be "directly perceived" [6]. The graph is then animated to show time-dependent behavior of circuits. The principle of the visualization is that *the given circuit diagram is used as a 2D schematic "ground plan" of a graph representing both voltage and current*. The graph is then "lifted" into the third dimension by *encoding node voltage levels* as the height of the node above the ground plane and by *encoding current through a conducting path* as height of a shaded area below the path. Power (the product of voltage and current) is represented as an arrow above the circuit graph (figure 7). The visualization can be described as an attempt to merge circuit topology and circuit variable states into a single graph or "graphic metaphor" [5]. It has been implemented as an add-on package to *Mathematica* [28] and is accordingly not freely available.

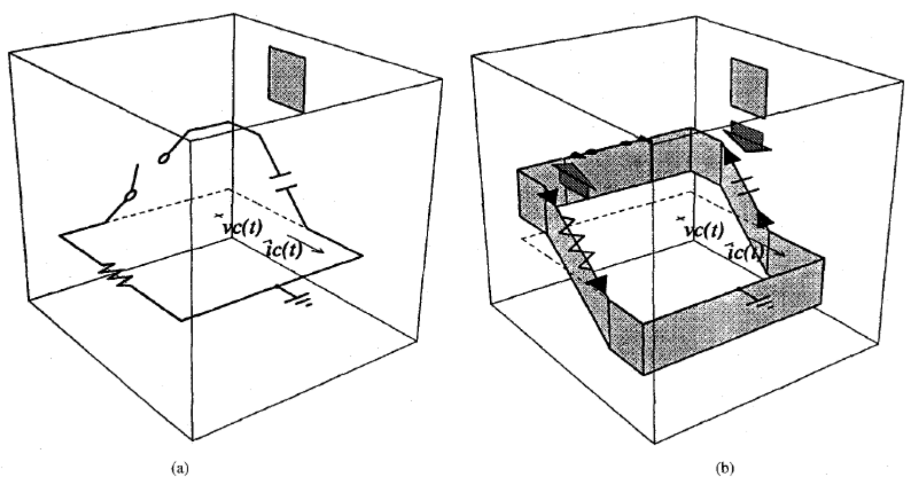

Figure 7: 3D visualization of voltage, current and power of a RC circuit (a) prior to switch closure with initial energy stored in the capacitor and (b) visualization of the circuit immediately after closing of the switch. Source: [5; 6].

Although the initial findings [5; 6] suggest an improvement for student learning (for 80% of the students), it should be investigated whether it is really an improvement over the alternative of interpreting multiple graphs (one for each variable as in figure 5). The graph also appeals to the fluid flow analogy that has been shown to lead students into misconceptions and this should be a source of skepticism about the benefits of the 3D graph. Another source of skepticism is that the perceptual benefit of integrating many variables into "one picture" is not always a conceptual improvement, because the analytical separation of each variable is still necessary for understanding circuit behavior.

The development cost of producing stand-alone *multimedia* applications for higher education is considerable, and multimedia instruction is often stipulated as the optimal support for modern engineering education, although it is not always carried out [10]. It is therefore comforting to point out that the real benefit of "multimedia" instruction is not necessarily due to the so-called *modality effect* of combined audio-visual communication, but also a result of combining *multiple representational forms* like the combinations of graphs, diagrams and explanatory text used in the educational tools discussed here in the context of electronics. Student's active learning of the content does furthermore not follow automatically from *free exploratory use* of the tools of e-learning (as it is sometimes assumed in "problem-based learning"), but should be considered as dependant on *specific instructions and scenarios of use*, i.e. an educational framework that specifies how students should be confronted with conceptual difficulties of the content (cf. the didactic problems discussed above), how they should collaborate and discover conflicting conceptualizations and results etc. Finally we should remember the primary concern of CDIO with regard to active learning, i.e. that student should be exposed to hands-on experiences related to practical engineering issues. This is accomplished in conjunction with the elements of e-learning by having students reconstruct some of their simulated circuits as physical circuits using wires, components and breadboards (figure 8).

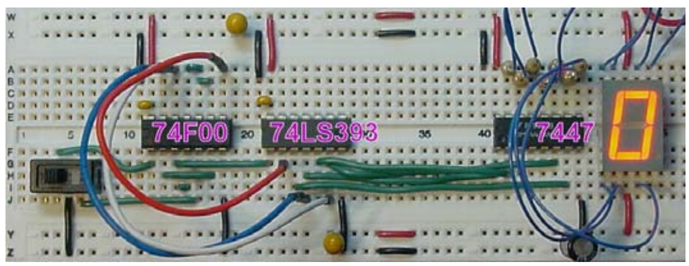

Figure 8: Breadboard for hands-on circuit construction

Conclusion

A number of didactic problems in learning electricity and electronics have been discussed in the context of a CDIO-driven revision of introductory courses in analogue and digital electronics on the bachelor engineering study in information technology at the Technical University of Denmark (DTU). It is argued that specific didactic problems can be heuristically linked to specific e-learning solutions, because it is possible to specify the kind of cognitive support required (e.g. considering simultaneous variables of electrical circuits) and the support provided by different e-learning techniques (e.g. animation). It is hoped that the relevance of e-learning techniques, embedded within relevant scenarios of use, can be introduced with more emphasis within CDIO, since it is seen as a complementary strategy to the main focus of CDIO with regard to the standard of active learning, i.e. the CDIO focus on design-build experiences and physical constructions. In many modern branches of engineering, like information technology and software engineering, virtual constructions are a primary concern in education as well as research.

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Biographical Information

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Jens Sparsø is a Professor in computer science and engineering at the department for Informatics and Mathematical Modeling at the Technical University of Denmark and he is director of studies for the E. Eng. in IT study program. His current research activities are within application specific computing structures and processors, low power design techniques, design of asynchronous circuits and systems, and communication structures for systems-on-chip (i.e. Networks-on-Chip).

Tom K. Johansen is an Associate Professor at DTU Electro at the Technical University of Denmark and he will be teaching on the revised course in introductory electronics referred to in this paper. His research areas include the modeling of HBT devices, non-linear circuit analysis, millimeter-wave integrated circuit design, and electromagnetic simulation.

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