Special Issue

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Introduction and Outline of the Special Issue on Circuits and Systems Education: Experiences, Challenges, and Views

1. Introduction

Whether it is the power grid, the telephone network, or the chip of a microprocessor or a mobile phone, all these are some of the most complex man-made systems that affect our daily life. Yet, the basic circuits and systems methods that are crucial for the specification, design, construction, and maintenance are mostly hidden or considered to be self-evident to the wider public and even to some engineers. Hence, in electrical engineering education, the topics related to circuits and systems still should play an important role in the future. However, various current developments challenge the role of circuits and systems (CAS) and, hence, it was considered important to clarify it, learn from various examples, and devise visions for the future. All these issues were discussed during a one-day workshop in May 2008. With this special issue, we wish to share these experiences and views, stimulate further interactions and role models, and prepare plans for future cooperation.

2. Content and Role of Circuits and Systems

It is not so easy to define what we consider by circuits and systems and this definition and scope may still be rather specific. Hence, we attempt to describe it from few perspectives. We can refer to the field of interest as stated by the IEEE Circuits and Systems (CAS) Society: "The theory, analysis, design (computer aided design), and practical implementation of circuits, and the application of circuit theoretic techniques to systems and to signal processing. The coverage of this field includes the spectrum of activities from, and including, basic scientific theory to industrial applications." The CAS Society has 16 technical committees working on various aspects of this mission (http://www.ieee-cas.org/). It is also interesting to look at the role of CAS from a historical perspective. We here briefly review the history of the CAS education [1]–[4]. It has been generally acknowledged that around 1930 an understanding of circuits based on mathematics and physics principles was gradually introduced in the electrical engineering curricula. It was also appreciated by industry. In 1953, Ernst Guillemin (a great educator: http://www.eecs.mit.edu/great-educators/guillemin.html) wrote [5], "linear, passive, lumped, finite, bilateral circuit theory is the electrical engineer's bread and butter. [The student] needs to know this subject before he tackles any of the other subjects in the curriculum." However, Guillemin insisted that the subject must be taught in a way that will provide a student "with basic concepts and ways of thinking that will not become obsolete throughout the rest of his undergraduate and graduate years." In 1984, Mac Van Valkenburg [6] reviewed fifty years of teaching circuits (1934–1984) by reviewing textbooks on circuits used in the USA. His paper indicated several landmark texts, such as [7], that are mathematically founded. However, reference [7] and even several updates such as [8] have been now abandoned by most schools. Of course, there are many excellent books written about basic circuit theory with slightly different flavors. However, the main ideas remain the same. Van Valkenburg's paper [6] offers no clear prediction about the next fifty years: "After more than a half century at both the undergraduate and graduate levels, it might be expected that common agreement would have been reached on what should be taught [in circuit theory]. This is not the case at all, as you must know. A new approach might appear tomorrow and sweep the field. Surely some future treatments will make the use of the computer and offer courseware. With this uncertainty, we have to face the next half century". Today, almost 25 years after this statement was made, we can confirm that there has been no such sweeping view in the field. The role of computers and computer aided design has indeed pervaded, but has not reversed the field of circuits and systems. In the frequently referred Circuits and Filters handbook [9], edited by W. K. Chen, a comprehensive overview of this field is given in thirteen

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parts that are outlined here. Such an enumerative list gives a detailed atomic view on the individual topics that may be covered in various courses and trajectories of education at various places.

PART I, MATHEMATICS: Linear Operators and Matrices, Bilinear Operators and Matrices, The Laplace Transformation, Fourier Series, Fourier Transforms and the Discrete Fourier Transform, z-Transform, Wavelet Transforms, Graph Theory, Signal Flow Graphs, Theory of Two-Dimensional Hurwitz Polynomials.

PART II, CIRCUIT ELEMENTS, DEVICES AND THEIR MODELS: Passive Circuit Elements, RF Passive IC Components, Circuit Elements, Modeling and Equation Formulation, Controlled Circuit Elements, Bipolar Transistors (BJT) Circuits, Operational Amplifiers, High-Frequency Amplifiers.

PART III, LINEAR CIRCUIT ANALYSIS: Fundamental Circuit Concepts, Network Laws and Theorems, Kirchhoff's Voltage and Current Laws, Network Theorems, Terminal and Port Representation, Signal Flow Graphs in Filter Analysis and Synthesis, Analysis in the Frequency Domain, Tableau and Modified Nodal Formulations, Frequency Domain Methods, Symbolic Analysis, Analysis in the Time Domain, State-Variable Techniques.

PART IV, FEEDBACK CIRCUITS: Feedback Amplifier Theory, Feedback Amplifier Configurations, General Feedback Theory, The Network Functions and Feedback, Measurement of Return Difference, Multiple-Loop Feedback Amplifiers.

PART V, NONLINEAR CIRCUITS: Qualitative Analysis, Synthesis and Design of Nonlinear Circuits, Representation, Approximation and Identification Transformation and Equivalence, Piecewise-Linear Circuits and Piecewise, Linear Analysis Simulation, Cellular Neural Networks, Bifurcation and Chaos.

PART VI, DISTRIBUTED CIRCUITS: Transmission Lines, Multiconductor Transmission Lines, Time and Frequency Domain Responses, Distributed RC Networks, Synthesis of Distributed Circuits.

PART VII, COMPUTER-AIDED DESIGN AND OPTIMIZATION: Modeling of Circuit Performances, Symbolic Analysis Methods, Numerical Analysis Methods, Design by Optimization, Statistical Design Optimization, Physical Design Automation, Design Automation Technology, Computer-Aided Analysis, Analog Circuits Simulation.

PART VIII, ANALOG INTEGRATED CIRCUITS: Monolithic Device Models Analog Circuit Cells, High Performance Analog Circuits, Broadband Bipolar Networks, RF Communication Circuits, PLL Circuits.

PART IX, THE VLSI CIRCUITS: Digital Circuits, Digital Systems, Data Convertors.

PART X, DESIGN AUTOMATION: Modeling Languages for AMS, RF & MW Modeling, Internet Based Micro-Electronic Design Automation Framework, System-Level Design, Synthesis at the Register Transfer Level and the Behavioural Level, Embedded Computing Systems and Hardware/Software Co-Design, Design Automation Technology Roadmap, Performance Modeling and Analysis in VHDL.

PART XI, PASSIVE FILTERS: General Characteristics of Filters, Approximation, Frequency Transformations, Sensitivity and Selectivity, Passive Immittances and Positive-Real Functions, Passive Cascade Synthesis, Synthesis of LCM and RC One-Port Networks, Two-Port Synthesis by Ladder Development, Design of Resistively Terminated Networks, Design of Broadband Matching Networks.

PART XII, ACTIVE FILTERS: Low-Gain Active Filters, Single-Amplifier Multiple-Feedback Filters, The Current Generalized Immittance Converter (CGIC) Biquads, Higher-Order Filters, Continuous-Time Integrated Filters, Switched Capacitor Filters.

PART XIII, DIGITAL FILTERS: FIR Filters, IIR Filters, Finite Wordlength Effects, Aliasing-Free Reconstruction Filter Bank, VLSI Implementation of Digital Filters, Two-Dimensional FIR Filters, Two-Dimensional IIR Filters, Symmetry and 2-D Filter Design.

This text contains most topics related to circuits and filters, from rather basic subjects, which are close to applied mathematics, to quite specialized topics typically offered in graduate engineering courses. However, the topics related to systems theory are limited. Since the Second World War, in the area of systems we have witnessed a shift from transform methods of Laplace transform and z-transform towards state-space based methods that employ linear algebra. Comprehensive textbooks and reference material have been written on linear systems [10]. However, this material is not frequently used and is more oriented towards control theory. In many electrical engineering departments, the basic circuits and systems courses have been reduced. Nevertheless, they still play an important role in the engineering curricula. The basic circuits and systems courses are nowadays designed based on the courses in mathematics (linear algebra and differential equations) and physics (electricity and electromagnetism). They have links with signal processing and control theory. A basic CAS course contains Kirchhoff Voltage Law (KVL), Kirchhoff Current Law (KC), Thévenin theorem, Norton theorem, Tellegen theorem, concepts of energy and passivity, graph theory, circuit analysis, filter design, and concepts of impedances and hybrid parameters. Furthermore, they introduce concepts of continuous as well as discrete time systems impulse response, transfer function, stability, poles, zeros, time constants, Bode diagrams, and interconnections. Even though these topics are considered to be essential in electrical engineering education, they are often scattered or merged with other courses such as courses in digital signal processing or control. These relationships are outlined in Figure 1.

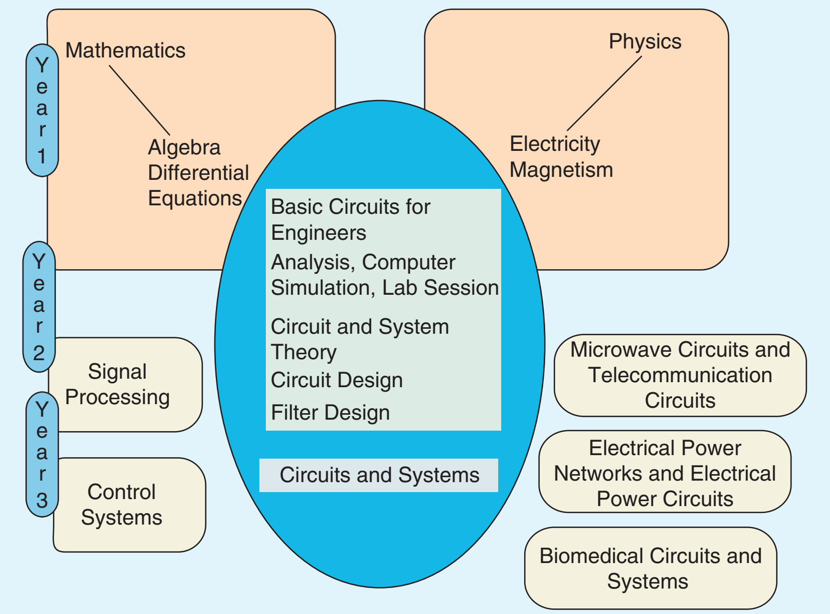

Figure 1. Links between circuits and systems courses with related courses in electrical engineering.

3. Current Issues and Developments in Circuits and Systems

Based on the previously discussed reflections and the experiences of the participants of the workshop, we can address the current issues and developments in CAS education.

We can state that the *topics covered in CAS education* are rather stable and common subjects in the education of electrical engineers. However there are several issues that affect their role. Engineers currently face increasingly complex systems and circuits and, hence, need additional insights and advanced tools for designing circuits. Furthermore, there is an increased role of computers and computer-aided tools such as SPICE and MATLAB and the use of the web and wikis. However, it is fair to say that methods of circuit analysis are not bypassed by simulations and that they complement each other. Basic concepts and insights do not become obsolete and are even more needed for analysis of complex systems. Moreover, there is increase in importance of nonlinear circuits and systems. While they were in the past considered to be curiosities that might be discussed in a final year graduate course, systematic employment of nonlinearities occurs nowadays in learning systems, sigma-delta modulators, cellular neural networks, and chaotic systems.

We note here several questions and open issues that are related to *the educational process of CAS topics*:

- How can the educational process capture the attention of the students and their motivation?
- Students in various parts of the world may be different from those of some years ago, and hence may need distinct ways of introducing the topics in the area of circuits and systems.
- Is the link between research and teaching in CAS still important?
- Is balance between theory, design, simulation, practice, and experimentation still required? Are hardware experiments still valuable or is software sufficient? What is the role of simulation tools such as SPICE and MATLAB?
- Should circuits and systems be taught jointly or in sequence? Should teaching discrete time systems be followed by continuous time systems or vice versa?
- Can one find good textbooks and reference materials or is there a need for new texts, updates, or other media (such as wikis).

We address some questions and open issues that deal [11] with *the relation between the society, the educational process, and the CAS topics.*

- The role of CAS education has drastically changed with the advent of computers and the Internet. New challenges such as environmental issues, energy shortages, and globalization offer new opportunities for CAS. Hence, when students learn about circuits as networks containing components and exhibiting dynamical behavior, they build a conceptual and a practical insight into systems. This can serve as an ideal basis for understanding various issues related to complex systems in other fields of technology, such as biology, world economy, climate, and environment systems. This link may be used to motivate students and to broaden their views.
- Can CAS topics be used for teaching students to understand the impact of engineering on society and the ethical issues related to the use of technology in society?

- There is a serious shortage of engineers. Hence, attracting students to engineering should begin early. Can the field of CAS provide examples that are fun for twelve-year old kids, stimulate their creativity, and motivate them to later begin engineering studies?

Moreover, several misconceptions circulate about CAS education:

- CAS topics are mature, basic, and generic for the field of electrical engineering and, hence, any faculty member in electrical engineering can teach them.
- There is no need to introduce circuits or mathematics of circuits and systems (linear algebra, differential equations, Laplace, Fourier, and z-transforms).
- There is no need to study CAS concepts such as KVL, KCL, modified nodal analysis (MNA), transfer functions, impedances, Bode diagrams and one should only learn to simulate circuits using SPICE and/or MATLAB.
- Industry is not interested in concepts and methods of CAS but, rather, in electronic products and services.

In order to address various questions and misconceptions, it was felt necessary to bring together different partners: instructors with diverse experiences, students or recent graduates (GOLD members), and industry. Hence, a one-day workshop was organized in Seattle at ISCAS 2008 with approximately twenty five participants with experience in CAS education (see Figure 2). Several participants currently in academia had previous industrial experiences. The teaching experience of the participants included topics on circuit theory, communication networks, signal processing, system theory, and communications.

4. Findings of the Workshop

During the workshop, the problems, issues, valuable approaches, and recommended actions were extensively discussed. The details of the presentations and the discussions are available from the workshop webpage (http://www.esat.kuleuven.be/sista/CASeducation workshop2008).

The findings and common understandings across the regions and the experiences were remarkably convergent and mutually stimulating. The participants reached consensus on the following main views and conclusions:

The skills and knowledge needed by industry.
The industrial problems an engineer is expected to solve today in industry are of a different nature compared to the past. In the past, the tasks were better-defined and had a longer lifetime. Today an engineer should be a team player in a multi-sited environment. In the new industrial environment, an engineer is expected to have:

- good knowledge and understanding of the basics
- flexibility to work on various projects
- broad knowledge
- good communication skills
- to be able to apply his/her skills in practice.

The students: [12]–[14]
The younger generation has not tinkered and young people are impatient. Since their experience is that everything takes place with pushing a button, they expect immediate gratification. They are familiar with software and the real world is somewhere else. Hence, at most places, one experiences a lack of interest by students in traditional circuits courses. This converges with the observations made by motivational psychologists in most countries that less than 20 % of the student population is strongly driven. Most of the students need to be motivated from "inside" with hands-on experience in parallel with the theory that is taught. Circuits and systems should be "fun". Hence, the first lab they will encounter must be a circuit's lab rather than a

Figure 2. Participants in the CAS Workshop, Seattle, Washington, May 2008.

software one. A hands-on approach lab will bring them in contact with the real world. The lab must be fun and motivational. Exciting their motivation is a significant step. The lab must make connections with applications and other courses.

The learning process from the point of view of the student.

Learning is a process from the "tabula rasa" state of the student to the state of discovering the knowledge. There are different types of students who differently engage in this process. Furthermore, there are also different types of professors' perception of the education process. The "René Magritte's pipe syndrome" states: what is taught in classrooms is not the real system and the real world is sensed in the lab with a hands-on approach.

Several participants emphasized the need today for a design-oriented analysis approach: a shift from "know-how" to "know-why". Additional design-oriented courses need to be offered sooner in the engineering programs. Students should also develop skills for mathematical modeling and formulation of various systems concepts. This should be achieved in a pedagogical manner.

The topics of circuits and systems and their scheduling

Most workshop participants were convinced that circuits and systems remain to be very important for education of electrical engineers and for their later careers. Most agree that we should teach continuous systems first followed by discrete systems and justified it by the fact that the world we conceive is continuous.

The teaching process itself can benefit from good experiences.

Teaching itself should be attractive and should stimulate the thinking process. Several actions may be taken in order to stimulate students' attention:

- carefully designing teaching "structure"
- developing geometric interpretations of the various concepts
- providing examples from applications
- including historical facts to help reflect the origin of the field and introduce open problems.

Interesting education-related information is available from the Richard Felder's website: http://www4.ncsu.edu/unity/lockers/users/f/felder/public/.

The importance of logistics

Small universities and, in particular, those in developing countries need freely available educational material, including video-recorded lectures. It is also of importance to synchronize theory and laboratory exercises. Furthermore, there is need for modern tools and integrated learning platforms for teaching circuits.

Recommended actions:

- Establish the CAS Society Education and Outreach Technical Committee and issue an open call for active participation.
- Prepare a Special Issue of the *CAS Magazine* reporting experiences and adopted teaching models.
- A position paper to be generated by the CAS Society Education and Outreach Technical Committee.
- Develop a dedicated website to collect material related to the education issues.
- Establish collaborations with the IEEE Education Society.
- Advertise initiatives in *CAS Magazine*, CASS e-newsletter, and the *IEEE Transactions on Education*.
- Appoint CASS representatives to other IEEE Societies to observe and report on relevant discussions.
- Enrich the CAS Society Distinguished Lecturer Program with speakers on topics related to education.
- Work closely with regional CAS Society Vice Presidents and regional Chapters.
- Develop a series of video recordings of lectures and related educational material and enlist help from the CAS Society.
- Organize a discussion panel at ISCAS 2009.
- The CAS Society Education and Outreach Technical Committee should develop a list of objectives and tools with the goal to motivate students.
- Develop the CAS concepts inventory.
- Promote group-based design projects that promote active learning.
- Promote projects that "rattle things apart" and build systems for the first-year engineering students.
- Develop career trajectories in CAS.
- Promote ethics and professional conduct.
- Involve IEEE with the accreditation of academic programs.

In order to elaborate and consolidate these findings, conclusions, and actions, various presentations at the workshop were incorporated in the papers published in this special issue.

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Joos Vandewalle was born in Kortrijk, Belgium, in August 1948. He obtained the electrical engineering degree and a doctorate in applied sciences, both from the Katholieke Universiteit Leuven, Belgium in 1971 and 1976 respectively. From 1976 to 1978 he was Research Associate and from July 1978 to July 1979, he was Visiting Assistant Professor both at the University of California, Berkeley. Since July 1979 he is back at the Department of Electrical Engineering (ESAT) of the Katholieke Universiteit Leuven, Belgium where he is Full Professor since 1986 and the head of the SCD division at ESAT, which has more than 130 researchers. From August 1996 till August 1999 and from August 2003 till February 2005 he was Chairman of the Department of Electrical Engineering. From August 1999 till July 2002 he was the vice-dean of the Faculty of Engineering at the Katholieke Universiteit Leuven. In the second semester of 2002-2003 he was on sabbatical leave at the I3S laboratory of CNRS Sophia Antipolis, France. Since February 2005 he is a member of the Governing Board of Science& Technology at the K.U.Leuven.

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He is a member of the editorial board of the *International Journal of Circuit Theory and its Applications*, *Neurocomputing, Neural Networks* and the *Journal of Circuits Systems and Computers*. From 1989 till 1991, he was associate editor of the *IEEE Transactions on Circuits and Systems*. He was Deputy Editor-in-chief of the *IEEE Transactions on Circuits and Systems Part I Fundamental Theory and Applications* from January 2002 till December 2003. Since 2001 he is a member of the Advisory Board of the International Journal on Information Security (IJIS). He was program chairman of ISCAS 2000 in Geneva, and for IJCNN 2004 in Budapest. He was Chairman of the NOLTA conference in Bruges in 2005. He was elected Fellow of IEEE in 1992 for contributions to nonlinear circuits and systems and in 2006 as Vice-President Technical Activities of the IEEE CAS Society. In 1991–1992 he held the Francqui chair on Artificial Neural Networks at the University of Liège and in 2001–2002 he held this chair on Advanced Data Processing techniques at the Free University of Brussels. He is also Fellow of the IEE (UK). He received several best paper awards and research awards. He is a member of the Academia Europaea and of the Belgian Academy of Sciences and its CAWET committee on engineering. He is a member of the Technology Committee of the Vlaamse Raad voor WetenschapsBeleid (VRWB).

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Dr. Trajković served as 2007 President of the IEEE Circuits and Systems Society. She was a member of the Board of Governors of the IEEE Circuits and Systems Society (2001–2003 and 2004–2005). She serves as Vice President Long-Range Planning and Finance of the IEEE Systems, Man, and Cybernetics Society (2008–2009) and served as a Member at Large of its Board of Governors (2004–2006). She is Chair of the IEEE Circuits and Systems Society joint Chapter of the Vancouver/Victoria Sections. She was Chair of the IEEE Technical Committee on Nonlinear Circuits and Systems (1998). She was Technical Program Co-Chair of ISCAS 2005 and served as Technical Program Chair and Vice General Co-Chair of ISCAS 2004. She served as an Associate Editor of the *IEEE Transactions on Circuits and Systems (Part I)* (2004–2005 and 1993–1995), the *IEEE Transactions on Circuits and Systems (Part II)* (1999–2001 and 2002–2003), and the *IEEE Circuits and Systems Magazine* (2001–2003). She is a Fellow of the IEEE.

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Efficient Algorithms for Signal Processing and System Identification, Prentice Hall 1993, the co-author of the best selling book *Pattern Recognition*, Academic Press, 4th ed. 2008, and the co-author of three books in Greek, two of them for the Greek Open University.

He is currently an Associate Editor of the *IEEE Transactions on Neural Networks*, the *IEEE Transactions on Circuits and Systems II* and a member of the editorial board of the *EURASIP Wireless Communications and Networking*. He has served in the past as an AE of the *IEEE Transactions on Signal Processing*, the *IEEE Signal Processing Magazine*, the *EURASIP journal on Signal Processing* and the *EURASIP Journal on Advances on Signal Processing.* He was the general chairman of EUSIPCO-98, the Technical Program co-chair for ISCAS-2006 and co-chairman of CIP-2008. He has served as President of the European Association for Signal Processing (EURASIP) and he is currently a member of the Board of Governors for the IEEE CAS Society.

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He serves as an IEEE Signal Processing Society Distinguished Lecturer. He is a member of the Greek National Council for Research and Technology and Chairman of the SP advisory committee for the Edinburgh Research Partnership (ERP). He has served as vice chairman of the Greek Pedagogical Institute and he was for four years member of the Board of Directors of COSMOTE (the Greek mobile phone operating company). He is a Fellow of IET and IEEE.

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Ljiljana Trajković

Regional Views and Experiences on Circuits and Systems Education

Teaching circuits courses to engineering students has been a topic of an ongoing debate over the past two decades. This debate continued during the Circuits and Systems Education Workshop held in conjunction with ISCAS 2008 in Seattle in May 2008. This contribution offers a collection of regional experiences and personal views presented at the CAS Education Workshop and at the Panel on Education in Circuits and Systems held at ISCAS 2008.

The contributions presented in this article by prominent educators in four distinct geographical areas address various issues relevant to CAS education and offer views and recommendations. The authors address current status of CAS education in each geographical region and offer suggestions for future improvements. While based on the presented material, opinions given in this contribution may have evolved based on the discussions held during the workshop. These suggestions also indicate ways how the CAS Society may help and get involved by developing valuable teaching tools and by sponsoring and encouraging educational projects and outreach programs.

A variety of topics is addressed, approaches debated, and remedies offered. They include:

- *General approach*: Basic circuits vs. digital signal processing (DSP first) debate and experiences from the Georgia Tech and the UC Berkeley experiments.
- *Targeted audience*: Need to design tailored circuits courses for a variety of engineering students with distinct majors.
- *Choosing the right text*: Finding the right text for a course among a myriad of available textbooks.

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