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Teaching Circuit Theory: 1934–1984

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Abstract—**Key developments in the teaching of circuit theory are traced over the past half century at the graduate and undergraduate levels.**

IN DESCRIBING historical developments in the teaching of circuit theory in the past half century, it seems necessary to review the educational climate in the early 1930's. The publication of the Wickenden report in 1929 was landmark in engineering education, stressing the teaching of fundamentals in contrast to the teaching of industrial practice and industrial design prior to that time. One of the recommendations of that report was the establishment of ECPD, now ABET, and the accreditation of engineering programs. The Wickenden position was not new; it had long been supported by leaders in our field such as Charles Steinmetz who used it as the theme of his AIEE presidential address in 1902. Also in 1929, industry began recognizing advanced degrees by adding 10 percent to the salary of engineers with a master's degree.

Thus in 1934, the year of AIEE's 50th anniversary, engineering education was ready for change. Prior to this time, a bachelor's degree with industrial experience was considered adequate for appointment as a professor to teach engineering. Then there was increased emphasis on the master's degree and even the doctorate for engineers. It was a climate in which a graduate program in a field such as circuit theory could flourish.

The person we can identify with the establishment of a group interested in circuit theory education is Vannevar Bush, a professor at MIT, Cambridge, MA. Although not now known to most circuit theorists, Bush was then well known for his interest in education and for his pioneering research in computers. Bush had been a student of Arthur Kennelly of Harvard University, Cambridge, MA, and MIT, himself a pioneer in electrical engineering. Upon receiving his doctorate in 1916, Bush joined the faculty at MIT and thus became a colleague of William Wickenden.

At MIT, a number of men gathered around Bush who would themselves become well known, and these men created the milieu in which circuit theory thrived. Guillemin had first come to MIT as Bush's assistant in 1924, and it was Bush who arranged for Guillemin to receive a Saltonstall Fellowship that took him to the University of Munich, Munich, Germany, for his doctorate. Working with Bush, including the writing of an appendix for his book, was a young assistant professor of mathematics, Norbert Weiner. Assisting Bush in teaching was Murray Gardner who was later to write his own famous book. In 1930–1931, Wilhelm Cauer came to MIT from Germany to work with Bush and spent part of that year writing his own first book, *Filter Networks* (1931) [12].

There were graduate students then, even as today. Frederick Terman received his doctorate in 1925 working with Bush, and then returned to Stanford University and greatness; while at MIT, he wrote his first book with Franklin (1926) [25]. Otto Brune, famous for his contributions to realizability theory, was a graduate student at MIT who stayed on to assist Ernst A. Guillemin in teaching. Legend has it that Brune left MIT to return to his native South Africa for family reasons and there worked on standards at Pretoria. C. M. Gewertz's doctoral thesis left its mark. It took 257 journal pages to print it, it consumed the entire 1933 volume of the *Journal of Mathematics and Physics*, and rather than reprints, the publisher issued it as a textbook (1933) [28]. Gewertz left MIT to teach in Thailand, later in Sweden.

Thus under Bush, MIT became an early center for the teaching of circuit theory. A similarly visible center was established at Ohio State University by William Everitt with emphasis on communications. Some of his students who later gained fame were John Ryder of Michigan State,

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Edward Jordan at University of Illinois, and Karl Spangenberg of Stanford University, CA. Both groups maintained close liaison with the Bell Laboratories, then located in New York City, a world center for research in theoretical and applied circuit theory.

The Formative Years

A significant event in our history was the publication of Bush's *Operational Circuit Analysis* (1929) [9] which brought together results obtained since the method was first introduced by Oliver Heaviside in 1901. This book was used as a textbook in many electrical engineering programs. Other books that were more nearly research monographs were those of Carson (1926) [11] and Berg (1929) [4]. For the decade of the 1930s graduate courses were established on operational circuit analysis or sometimes Heaviside's operational calculus.

The teaching of the course at MIT was soon turned over to Murray Gardner as Bush pursued other interests. Bush was later drawn into administration first as Vice President of MIT, later as President of the Carnegie Institution of Washington. He served as head of the important Office of Scientific Research and Development during World War II.

In 1928, Guillemin was assigned to develop a graduate course in "Advanced Network Theory including the Design of Electromagnetic Wave Filters and Related Networks." The consequence of this assignment was the writing of two books entitled *Communication Networks* (1931), (1935) [30]. These two books were the basis of courses on communication networks for the next decade.

Developments During World War II

Although civilian students vanished during World War II and many faculty members left the university for research, important textbooks were published. The first of these was *Transients in Linear Systems* by Murray Gardner and John Barnes. The coverage of topics was similar to the book by Bush, but the Heaviside operational calculus had been replaced by the Laplace transformation, a significant event. Gardner had long been at MIT, Cambridge, MA, and Barnes taught there briefly after receiving his doctorate in mathematics at Princeton University. He later taught the Laplace transformation method to undergraduates at Tufts University Medford, MA, before going to University of California, Los Angeles. Gardner and Barnes' book was widely used in the US and it became familiar to most engineers. In the 1960s, I was with Barnes on a tour of a facility in the USSR, and our guide explained to Barnes that his book had sold three times the number of copies in the USSR than in all Western countries combined.

The other significant book written in this period was Hendrik Bode's *Network Analysis and Feedback Amplifier Design* [6]. First used as notes at Bell Laboratories and other industries, in appeared in textbook form in 1945. This book was a summary of the many contributions Bode had made to circuit theory, a compilation of important topics in the design of circuits, with and without feedback. Bode had joined Bell Laboratories after receiving his MA in mathematics in 1926 from Ohio State University. He was born in Madison, WI, and spent his early years in Urbana, IL, where his father was then a professor of education.

By the end of World War II, Guillemin had further developed his course to the point that he no longered used his *Communications Networks* [30] in his classes. His topic was now known as network synthesis. His material was well organized and ready for classroom use when he first gave the course after World War II, but it would not appear in textbook form for more than a decade.

Our Golden Era

At the conclusion of World War II, there was a backlog of potential graduate students, veterans of the War, engineers from industry, all anxious to pursue higher education. Many had been involved in new developments during the War: radar, sonar, control, communications, microwave systems. Never since have there been students so highly motivated to learn more theory to go with their application backgrounds. High priority was given to courses with mathematics content applicable to the study of systems.

I can write from personal experience as MIT began its Fall term in 1945. The enrollment for the course on *Transients in Linear Systems* was so large that three sections were required, each of the three crowding the classroom assigned. In the Spring of 1946, Guillemin's course on network synthesis was offered. It had been scheduled for a classroom holding 20 students, based on typical enrollments before the War. When 150 students showed up, it had to be moved to the largest lecture hall available. Similarly, large classes were characteristic at Stanford University where Tuttle taught network synthesis and Pettit amplifier theory, each to sections of over 100. The same thing must have happened elsewhere. These large enrollments continued, and similar courses spread to all universities at the graduate and later undergraduate levels.

This burst of interest and enthusiasm continued unabated for another 20 years. During this period, essentially all graduate students studied from books by Gardner and Barnes, Bode, Guillemin, or from a spate of new books that appeared with regularity.

Of the competitions for new textbooks, the most interesting was that for one on network synthesis. Many members of the faculty had started teaching such a course, armed with notes from the course at MIT, Stanford, or other universities. Guillemin's lecture notes seemed to me to be ready for publication in the Winter of 1946, but it took him until 1957 to put his book in a form he found satisfactory. At that time, many of Guillemin's former students and others were writing their own books, threatening to beat Guillemin. He wrote in his preface that "I just could not let that happen." The nearest competitor in retrospect was that from Tuttle (1958) [68]. But books for use, primarily at the graduate level, appeared by Balabanian (1958) [1], Weinberg (1962) [74], and Temes and LaPatra (1977) [64].

Another popular course that developed was in linear network analysis. An early favorite was that by Seshu and Balabanian (1963) [58], revised after Seshu's untimely death in an automobile accident as Balabanian and Bickert (1969) [2], and later by the same authors (1981) [3]. Gardner and Barnes received some competition from Weber (1954), (1956) [73]. New books appeared that followed the pattern established by Bode. The best of these, in that it extended and generalized the coverage, was by Kuh and Rohrer (1967) [44]. Others have appeared by Spence (1970) [60], Thomason (1955) [65], and Chen (1980) [13].

Network synthesis spans a domain extending from applied mathematics to applied problems, but there are many gaps between it and actual filter design. Courses to bridge this gap were based on textbooks such as Humphreys (1970) [38] and Blinchikoff and Zverev (1976) [5], the latter being unique in that it covers topics in the time domain as well as the frequency domain. Other books provide extensive tables to make design practical including Geffe (1963) [27], Zverev (1967) [75], Christian and Eisenmann (1966) [14], and the fabulous compilation by Saal (1979) [55].

Two important books were written to cover the important cases of linear active circuits restricted to *RC* elements by Huelsman (1968) [35] and Mitra (1969) [50]. If we designate active *RC* circuits which use only the operational amplifier as an active element to be analog filters, then we have an increasingly popular area for study. Such filters are used alone or in conjunction with digital filters. Significant books have been written by Sedra and Brackett (1978) [57], Moschytz (1974) [51], Temes and LaPatra (1977) [64], Huelsman and Allen (1980) [37], and Ghausi and Laker (1981) [29]. The last named book has extensive material on the design of switched-capacitor filters.

In 1960, I wrote in a preface with conviction that "...no electrical engineering graduate is equipped to understand the literature or advanced practice without a knowledge of modern synthesis methods." This appears to have been true until about 1970 when events, primarily the widespread availability of inexpensive digital computers, brought about the beginning of the end of this Era. We cannot blame it all on the computer, for there are a number of natural causes. Consider the following:

(1) The study of linear systems involved such mathematical topics as linear algebra and complex variables, and new concepts such as state variables. Most of this material had moved from the graduate to undergraduate level.

(2) The technology developed during World War II was understood through studies of linear systems. New technologies appeared requiring knowledge of new subjects such as statistics and the mathematics of computers.

(3) Most research problems had been solved and that continuing soon reached the baroque stage of tieing up loose ends. The design of filters, for example, was fairly well reduced to the use of tables.

The Computer-Related Era

Very few disciplines permit one to conduct research on a single topic for a lifetime. Certainly engineering does not for there is a continual shift of interest in the direction of real-world problems. The development of large and inexpensive computers and computational facilities beginning around 1970 has had a profound effect on our field. We are in the new formative stages as we enter this era, but it appears that some of the major problems for circuit theorists in the computer-related era will include the following:

(1) Computer-aided design, especially of VLSI circuits.

(2) Layout and routing problems, a revival of some aspects of graph theory.

(3) Optimization strategies, especially used in conjunction with (1) and (2).

(4) Techniques of digital signal processing.

In the design of VLSI circuits, the classic is clearly the textbook by Mead and Conway (1980) [49], with new books now appearing such as the one by Muroga (1982) [52]. The standard textbook on computer-aided design is that by Chua and Lin (1975) [16]. Other books include that by Calahan (1972) [10] and two chapters of Balabanian and Bickert (1981) [3]. It is well known that many books appropriate to the new era are in preparation, some nearing publication. Time will tell which become the new classics.

Undergraduate Courses

Books for undergraduate education have traditionally played a different role than those for graduate education. Their intended purpose is twofold: provide background for courses that follow, and present material relating to the profession. Such books often lag well behind state of the art because of the preference for well-established material.

Entering this half-century, there were a limited number of books on circuit theory. Consider Bryant and Correll, *Alternating Current Circuits* which appeared in its second edition in 1931 [7]. Its content was typical for this era: 30-percent fundamentals, 28-percent three-phase, 30-percent transmission lines, and 12-percent nonsinusoidal waveforms.

Although the fields of circuit theory and transmission lines are now separate and distinct, such was not the case in the 1930's. Transmission lines were an important research and application topic. For example, the book by Carson (1926) [11], a record of lectures given at the University of Pennsylvania, Philadelphia, devotes half of its chapters to operational calculus applied to transmission lines. At the time Bush wrote his book cited earlier, his title was Professor of Electrical Power Transmission, and the first two years of Guillemin's lifelong stay at MIT were spent with Bush working on transmission-line problems.

The association of circuits with a field of application was usual. Two textbooks by Dawes were widely used. Titled *Electrical Engineering, Vol. I, Direct Currents* (1920) [19] and *Vol. II, Alternating Currents* (1922) [19], the first chapters were on circuits, the remaining chapters were devoted to machinery. These were my first introduction to circuits in 1941; my books bear the price tag of \$4. In addition, I studied from a book by Timbie and Bush (1922) [66] which covered circuits, electric and magnetic fields and primative electronics. Yes, this is the same Vannevar Bush cited earlier!

Another source of education in circuit concepts was available in the book by Everitt titled *Communications Engineering* (1932) [23] which was usually taken in the senior year. It was in this book that a statement of Norton's theorem first appeared. The first half of this book is on circuits, a general and modern treatment of the subject. Everitt had close ties with Bell Laboratories at the time the book was written through summer employment and consulting, and was influenced by important books of this era by K. S. Johnson (1925) [40] and Franklin and Terman (1926) [25] which gives a simple treatment of filter theory.

When Kerchner and Corcoran's book *Alternating Current Circuits* appeared in 1938, they could write in their preface that it was intended for juniors as required by "most engineering colleges." This book had the same title as earlier books and the same contents with two exceptions: a new chapter on wave filters and one on transients. It was natural that filters should appear since they were developed in conjunction with transmission lines by Wagner and Campbell in 1903, and the *m*-derived filter had been first described by Zobel in 1923. A 15-year lag is not bad! The chapter on transients proved to be a precursor of whole books on the subject.

After the end of World War II with bulging undergraduate enrollments, engineering educators had a choice of only a few books on circuits. Kerchner and Corcoran emerged as a favorite in the main stream, along with Tang (1940) [63] and later Reed (1948), all on ac circuits. There also emerged a tradition that three courses were necessary for the electrical engineer: dc circuits, ac circuits and transients. In addition, most students studied from an updated *Communications Engineering* by Everitt and Anner (1956) [24].

Few educators were prepared for the bombshell that hit the circuits community in 1953 with the publication of Guillemin's *Introductory Circuit Theory* [32]. The message was clear: you have been doing it all wrong, and here is the way to do it right. Guillemin lucidly explained his position in a 15-page preface, followed by the first chapter on topology, followed by chapters of topics that seemed too difficult for ordinary students when compared to Guillemin's sophomores at MIT. The book had a great impact, but did not itself enjoy great popularity.

One of the universities that did adopt Guillemin was Purdue University, Lafayette, IN. It was used for a number of years, followed by using Scott (1960) [56]. Following this, two Purdue professors were assigned to produce a new book which would be a blending of the new and the old, and the result was the book by Hayt and Kemmerly (1962) [34] which has been the mainstream textbook since then. The first edition of Hayt and Kemmerly followed Guillemin in avoiding the Laplace transformation, preferring to use the exponential function e^{st} instead. By the second edition (1971), the Laplace transformation was in place and has remained there since. The success formula that has persisted to this day is: resistive circuits, transients, sinusoidal steady state, complex frequency, Fourier and Laplace methods.

The teaching of the Laplace transformation followed the popularization of the subject at the graduate level following World War II. This development had been widely anticipated. Bush expressed the hope in his preface that operational analysis would become part of undergraduate study. The preface to the book by Gardner and Barnes related that Barnes had taught the subject to undergraduates at Tufts University. My personal recollection is that it was used everywhere by 1948, but it took a number of years to appear in textbooks. It was used in my textbook (1955) [69] as the basis for unifying dc, ac, and transient circuit behavior as well as elementary network synthesis. It was similarly used for unification by Pearson and Maler (1964) [53].

A landmark textbook which has influenced the teaching of circuits was that by Desoer and Kuh (1969) [20]. It was written with great mathematical care and has proven popular in classes of students with superior mathematical preparation. It contains a rigorous derivation of the properties of circuits, but breaks with tradition in that it excludes consideration of the properties of signals.

A bold experiment in the teaching of circuits was the treatment of nonlinear network theory by Chua (1969) [15]. It was used to teach sophomores at Purdue for a number of years, including a simulation laboratory, but lost favor when Chua moved to California.

Authors of textbooks on circuit theory have not lacked imagination in how the subject should be treated. One of the most widely used books on elementary circuits was due to Skilling (1957) [59]. It is best known for its lucid explanations for which Skilling had become famous; it was the last book to include a treatment of the *m*-derived filter. Some authors have agreed with Guillemin that a proper student of circuit theory must begin with mathematics. Ley, Lutz, and Rehberg (1959) [47] start with topology and matrix methods, and Peskin (1961) [54] begins with chapters on the Fourier and Laplace transforms followed by one on complex variables and the evaluation of the inversion integral. Trick (1977) [6[illegible]] approached the subject with a careful blending of circuit theory and solid-state electronics. Durney, Harris, and Alley (1980) [22] emphasize practical matters such as modeling, physical interpretation, graphical methods, checking. Steiglitz (1974) [61] considered only the discrete signal case in a book intended to be used with other books on circuits. Strum and Ward (1973) [62] wrote their book featuring carefully worked out examples. Several books have combined computational methods with topics in circuit theory, the two most enduring being by Huelsman (1972) [36] and Director (1975) [21]. Cruz and Van Valkenburg (1974) [17] gave early emphasis on signals followed by a consideration of circuits. Johnson, Hilburn, and Johnson (1978) were the first to incorporate the op amp throughout their book. Van Valkenburg and Kinariwala (1982) [72] stressed design with three chapters on op amp circuits and one on switched-capacitor filters. And so experimentation goes on and on.

The crowded curriculum still sometimes permits a second course or electives. The book by Karni (1971) [43] has "intermediate" in its title. The first book for undergraduates on network synthesis was that by Kuh and Pederson (1959) [45] followed closely by Van Valkenburg (1960) [70]. Other books have covered synthesis topics including those by Kuo (1962) [46] and Karni (1966) [42]. Courses formerly on synthesis now are called analog filters using the op amp; such courses use books by Budak (1974) [8], Daryanani (1976) [18], Johnson (1976) [39], Lindquist (1977) [48], and Van Valkenburg (1982) [72].

Concluding Remarks

Clearly, I have written about education in circuit theory in the USA, and about books written in English. These are the developments with which I am most familiar. But I do know that similar things happened in other countries, that the role of Guillemin in the USA has its counterparts elsewhere including Cauer and Saal in Germany, Belevitch in Belgium, Kawakami and Ozaki in Japan, Bayard in France, Horvat in Yugoslavia, K. Simonyi in Hungary, Sigorskii and Tsypkin in the USSR. It will be interesting to tie all of these together in some future study.

Of the 700 or more books that have been published on circuit theory in the past half century, I have been able to cite only a few. I hope that I have selected those that have had some impact on the directions which education in circuit theory has taken, and I apologize in advance for any that I have neglected.

After more than a half century of teaching circuits at both the undergraduate and graduate levels, it might be expected that common agreement would have been reached on what should be taught. 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 use of the computer and offer courseware. With this uncertainty, we face the next half century.

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