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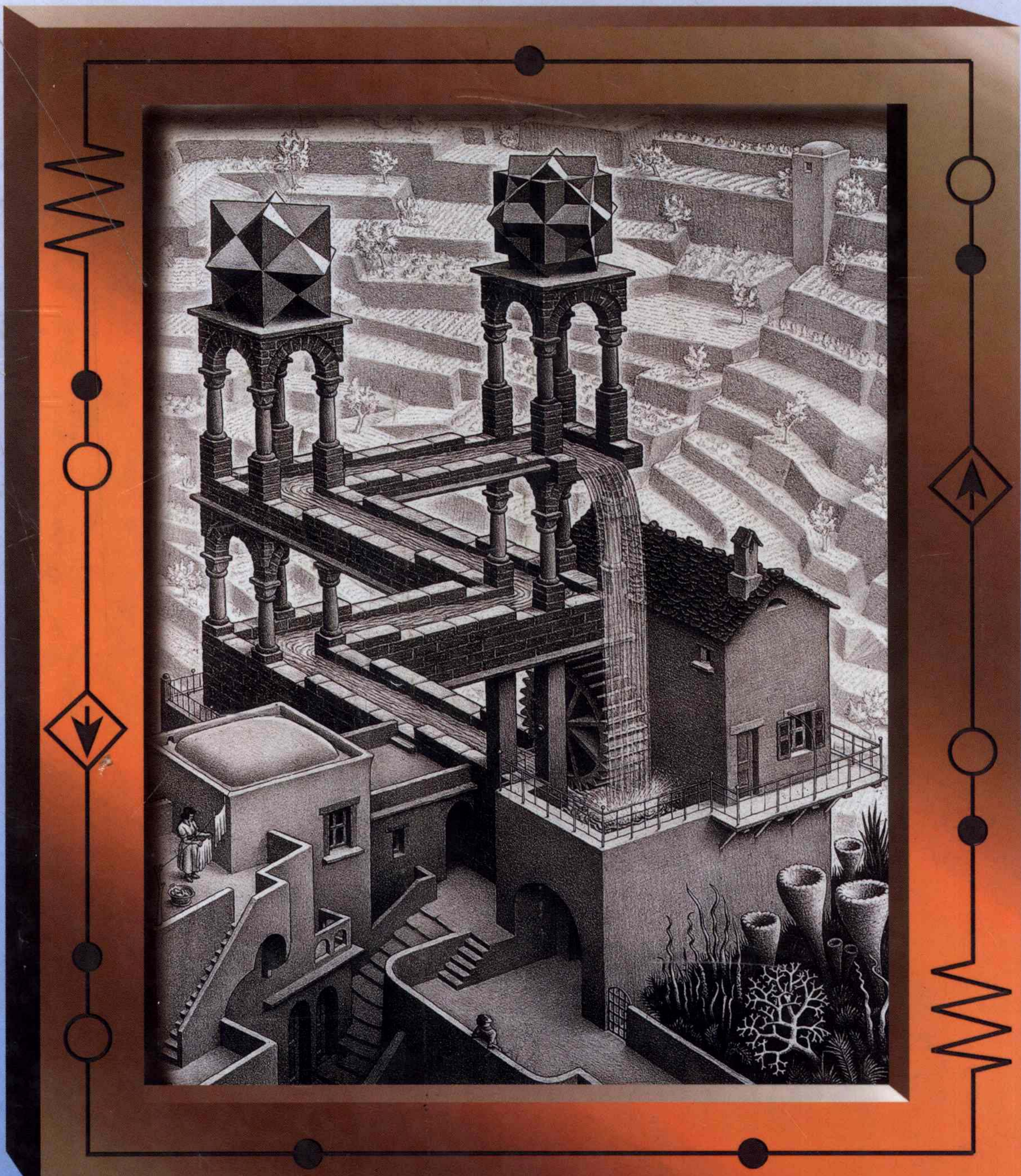
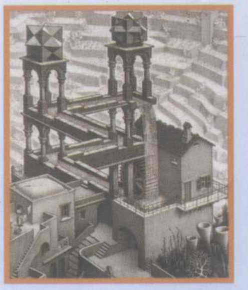
LINEAR CIRCUIT ANALYSIS



ARTICE M. DAVIS

ELECTRICAL ENGINEERING/CIRCUIT ANALYSIS



LINEAR CIRCUIT ANALYSIS

Artice M. Davis, San Jose State University

This book systematically builds students' analytical and problem-solving skills through a carefully graduated presentation of concepts, the use of detailed, copiously illustrated examples, and teaching approaches that present circuit analysis topics in a unified context. Chapters 1–3 introduce basic concepts of circuit analysis more deliberately and in greater detail than traditional texts, while establishing a solid mathematical foundation for the analysis and solution of problems. In Chapters 6–10, author Artice Davis presents a method of time domain analysis that unifies the three major divisions of circuit analysis (DC, AC, and transient analysis) based on the use of differential operators. In addition, from Chapter 1 onward, Davis presents circuit theories in the context of three fundamental qualities—time, voltage, and current—while emphasizing a practical, "applications-oriented" study of active circuits. As a result, this book provides students with a demonstrated mastery of problem-solving skills and an integrated knowledge of circuit analysis topics that effectively support their later studies in signals and systems, electronics, and control.

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This book is dedicated to the memory of ***Dr. Oliver Heaviside,*** F.R.S. (1850–1925), who developed the theory of differential operators used here. The theory was not understood by others of his day, yet it was later cited by the respected British mathematician Dr. Edmund T. Whittaker as "one of the three most important discoveries of the late nineteenth century." Dr. Heaviside's last home was a cottage high on a hill overlooking the bay in Torquay, Devonshire, England. On the gatepost there is a plaque dedicated to "Dr. Oliver Heaviside, mathematician and engineer" that cites his many accomplishments. When the author visited the site a few years ago, there was a crack in the plaque, which his fancy recalls as being between the words "mathematician" and "engineer." It is the author's sincere hope that this text will help mend the crack.

Preface

Chapter Outline and Notes to the Instructor

This book is intended for the undergraduate course in circuit analysis, customarily the first course taken by aspiring electrical engineers. For many students entering the field of electrical engineering, circuit analysis can be a rude awakening. It tests the depth of their background knowledge in mathematics and physics and carries a full load of serious analytical content. Typical texts for this course devote only a few pages to fundamental concepts (such as circuit topology, basic laws, and the why's and how's of network analysis) before plunging into the mechanics of solving complicated circuits. Students unable to make this transition quickly and easily are challenged to make sense of such basic ideas as equivalent resistance and current and voltage division, even as they struggle to master more advanced topics, such as Thévenin/Norton equivalents, time domain response methods, and the phasor analysis of circuits. As a result, many students who would benefit from a more gradual learning curve at the outset of the course are doomed to drop out of it, and out of the field of electrical engineering as well. *Linear Circuit Analysis* is designed to address this problem by enabling students to retain more concepts and skills in circuit analysis as they work through the early chapters so that they can complete the course with confidence and with a better awareness of how circuit analysis relates to succeeding courses in electronics, signals and systems, and control. The remainder of this preface will outline how that goal has been accomplished.

Part I (Dc Analysis)

In Part I, Chapters 1–3, basic concepts of dc circuit analysis are presented more deliberately and in greater detail than in traditional texts, while a solid mathematical foundation for the analysis and solution of circuit problems is established. Here is a small, yet significant example—one borrowed from the authoritative text *Classical Circuit Analysis* by Vitold Belevitch: *simply erase the body of each element in the circuit and the connected "islands" of conductor that remain are the circuit nodes.* Students are encouraged to do this exercise at the outset of their attack on a given circuit problem until node identification becomes second nature. Here's another example: the use of multiple ground reference symbols is introduced early, and circuits are occasionally drawn using this symbolism to prepare students for later courses in electronics. Still another example is the stress placed in Chapter 3 upon the idea of a subcircuit and the closely linked idea of an equivalent subcircuit. This forces students to come to understand these important ideas before they encounter the "big machinery" of nodal and mesh analysis in Chapter 4. I have often seen students fail, not only in this course, but in succeeding electronic circuits courses as well, because they have not grasped these basic ideas. Such a lack of understanding causes the student difficulty in dealing with simple series and parallel resistors, to say nothing of an active subcircuit exhibiting negative resistance. The topics often referred to as "circuit theorems," superposition and the Thévenin-Norton equivalents for instance, are presented before nodal and mesh analysis so that the student is not sidetracked from these important ideas by the lure of more general and algorithmic methods.

Linear Circuit Analysis bases its approach on three fundamental physical quantities: time, voltage, and current. These variables are defined operationally, that is, by specification of the measuring instruments and the procedures by which they are measured. All other variables are derived quantities; their definitions are based on the three fundamental quantities and mathematical formulas. For instance, power is defined as the product of voltage and current, and energy as the integral of power (the product of power and time). Therefore, the concept of mechanical work is not required. This approach has two very important advantages: it eliminates the physics prerequisite and it lends a practical flavor to the theory being developed because of its close connection with the way measurements are actually made in the laboratory.

Chapter 4 covers mesh and nodal analysis. There are some novel features here. For instance, each example is illustrated with several figures showing a circuit at different stages of analysis. Students are encouraged to make such drawings as a "preamble" to the writing of nodal and mesh equations. A carefully constructed node (and mesh) cataloguing scheme is introduced to assist students in making these drawings and in deciding how many (and where) equations should be written. In a later section of the development, an original technique of nodal and mesh analysis by inspection is developed that enables students to write the matrix form of these equations directly from the circuit diagram. Appendix A offers a "minicourse" on linear algebra, matrices, and determinants to complement the methods developed here. Selected portions should be either covered in lecture or assigned for home study. Though students have typically been exposed on several occasions to this material, they have not yet seen an organized development of it.

Chapter 5 is devoted to the analysis of active circuits. The topic has been postponed until this point to allow students enough time to become better acquainted with the basic ideas of circuit analysis before they encounter the complication of dependent sources. A novel method called *taping* is presented for analyzing circuits with dependent sources. The idea is to visualize a dependent source as having a label on it marked with the dependency relationship. One imagines a small piece of masking tape being placed over this label and a literal unknown value written on it. Because the v-i characteristic of the device is exactly the same as that of an independent source of the same type, one can then proceed to analyze the circuit just as if it only contained independent sources and resistors. After the circuit equations are written, one "untapes" the source and invokes the dependency relationship. This turns the analysis of active circuits into a procedure whose main subprocedure is the one already developed for passive circuits. Sections 5.1 and 5.2 were written so that an instructor can cover them before Chapter 4 if so desired. Section 5.3 requires a mastery of nodal and mesh analysis. Sections 5.4 through 5.6 deal with the op amp, and Section 5.5 is devoted to a careful explanation of the need for negative feedback and the conditions under which the ideal op amp model is valid. Section 5.6 discusses the derivation of models for electronic devices: diodes and bipolar junction transistors. Later in the text, all exercises, examples, and problems using op amps or transistors are marked appropriately with (O) and (T), respectively.

Part II (Time Domain Analysis)

Part II, Chapters 6–10, presents a method of time domain analysis that unifies the three major divisions of circuit analysis (dc, ac, and transient) based on the use of differential operators. This technique was developed in response to the question often posed by students when they are applying the classical theory of differential equations to determine the transient response of an RLC circuit: "Isn't there a general method for determining the arbitrary constants in the solution from circuit initial conditions?" A careful analysis reveals that there is—state variable theory—but, unfortunately, it is too complicated for the introductory circuits course. This seems to be the main reason that most introductory texts do not deal with circuit responses of higher order than second in the first course material.

The differential operator approach does not have this deficiency, and its development here from first principles means that a differential equations course is not a prerequisite (the only prerequisite is freshman calculus). The approach relies upon the fact that the inductor and the capacitor obey a generalized form of Ohm's law in the time domain and, therefore, that all of the methods previously derived for dc analysis continue to hold, just as they do for the computation of ac forced response using phasors. This has obvious pedagogical advantages, a major one being that the student uses the same techniques twice more after being exposed to them in the dc material. Though it is unusual for a course syllabus to permit the repetition of techniques while significant new material is being introduced, this benefit does accrue when one adopts the operator method of transient analysis. This method is straightforward, algorithmic, and easy to teach. It has been class tested for some time by the author and his colleagues and has been received very favorably by the students. The reason for this is probably due to the important fact that the operator approach is precisely the same as the Laplace transform method, except that no transform is required (with its attendant difficulties of dealing with improper integral convergence and the necessity of translating each problem into a completely different domain). The operator method proceeds just like the Laplace transform technique—including the partial fraction expansion—in a manner that is strictly algebraic for the waveforms normally encountered in circuit analysis. Students like this algorithmic and constructive approach, and it is not intrinsically limited to circuits of low order.

The material on transient analysis was written, however, with flexibility in mind. At the option of the instructor, transient analysis can be covered only through second-order circuits, with the remaining time domain material being postponed to the second course. In either case, the instructor should cover the basic ideas of impulse and impulse response in Chapters 6 and 7 because these computations replace the evaluation of arbitrary constants (in the classical approach) from circuit initial conditions. I have taught this material with both course organizations, and both work quite well.

Part III (Frequency Domain Analysis)

Part III, Chapters 11–14, develops the frequency domain viewpoint and methods of analysis. Chapter 11 deals with the phasor analysis of ac circuits. It was written so that an instructor can teach the material at any desired point after the material in Part I on dc analysis and thus does not rely upon the material in Part II on time domain analysis. There are several new approaches in this material, a notable example being the interpretation of complex power. Complex power is introduced with more physical motivation than usual, and a slightly different definition than the conventional one is given: it is defined as $S = \overline{V}^*\overline{I}$, rather than as the more conventional $S = \overline{VI}^*$, because the former has a number of notational advantages and creates no difficulties in application. Appendix B states and proves Tellegen's theorem, which is necessary for the discussion of conservation of complex power in this chapter (and for making the proof of solvability using the methods of Chapter 4 logically complete).

Chapter 12 starts with an overview of the frequency domain point of view motivated by the design problem of removing a signal from noise, followed by a detailed analysis of tuned circuits and a practical discussion of filter design. A new, rapid method for sketching Bode plots is presented here.

Chapter 13 develops circuit analysis techniques using the Laplace transform. Because the circuits and systems literature of the past half-century has used this notation, it is important that students today be aware of this different language. For those who have already covered the operator techniques presented in Part I, Section 13.0 is presented as a "quick fix" in the basic ideas and vocabulary. This section proves that the operator method is merely the time domain equivalent of the Laplace method and that one can interpret operator equations as Laplace-transformed equations by merely replacing p at each occurrence by s and simply eliminating all delta functions. The rest of the chapter develops the entire theory of circuit analysis using the Laplace transform in a more leisurely manner. It is written in such a way that an instructor can elect to cover it immediately after Part I on dc analysis if he or she wishes to use a Laplace orientation for transient analysis. Needless to say, there is quite a bit of duplication of material between this chapter and the methods already developed in Part II. A somewhat more sophisticated, though still largely intuitive, treatment of generalized functions (than was given earlier in Part I) is presented in the body of this chapter. Appendix C is a more rigorous mathematical complement that has been included for the instructor and the more analytically inclined student. It has previously been published only in the form of a paper that I delivered at a conference, and I felt that some would find it of use in a more accessible place.

The subject of Chapter 14 is Fourier analysis. The Fourier transform is defined to be the Laplace transform evaluated (either directly or as a limit) on the imaginary axis of the s-plane. The Fourier transform of periodic functions is derived, and this leads to the Fourier series representation. The important topic of spectrum analysis is covered, and the concept of negative frequency is discussed in a novel way. This discussion then leads naturally into a treatment of various types of amplitude modulation schemes, developed briefly as practical applications of transform theory.

Part IV (Selected Topics)

Part IV contains what I consider to be special topics, though other instructors might wish to cover them sooner than their placement in the book might indicate. This part contains only two chapters, the first on two ports and the second on transformers. Two ports are treated in somewhat more depth than usual in Chapter 15, in that discussions are given as to why some parameter sets fail to exist for a specific subcircuit. A rather extensive development of the application of two-port methods to the analysis of feedback systems is given. I feel that most texts fail to provide motivation for the study of two ports, and the analysis of feedback systems is a major application. This material is, of course, optional. If it were chosen for coverage, one could "download" a significant amount of material from succeeding electronics courses. The material on transformers in Chapter 16, too, is a bit different from the usual fare. It deals with the transient response of circuits having mutual inductance as well as with their more commonly treated ac steady-state behavior. A discussion of the reciprocity of transformers is given that is more sound than the usual one and is based upon a novel idea that only recently appeared in print in a professional journal.

In summary, this book uses differential operators to unify the treatment of the three major divisions of introductory circuit analysis. This student-friendly approach results in focused discussions of dc, ac, and transient analysis in a logical and parallel fashion. It presents methods for solving specific circuits in a concrete manner and then shows their abstract mathematical nature in a more general setting that makes the transition to linear systems easier for the student to understand. Discussion of the systems-level generality of the methods being developed is aided by the use of simulation diagrams. Finally, it seeks to help students retain concepts and problem-solving skills, and help instructors retain more students in the course, through a more gradual, careful, and systematically integrated discussion of the fundamental ideas underlying circuit analysis.

Instruction Support Materials

In addition to the Answers to Selected Problems at the back of the book, a complete solutions manual is available from the publisher.

Web-Based Interactive Study Guide

The CD-ROM bound into the back of this book contains a number of tools that are designed to help the student learn about circuits more effectively and that may aid students with different learning styles.

A CD-ROM icon (shown at left) is distributed throughout the book to indicate which examples are given treatment in the electronic files on the CD-ROM in the back of the book. The letters in the four quadrants on the icon indicate the kind of file(s): ML for MATLAB, MC for MATHCAD, EW for Electronics Workbench, and PS for PSPICE. Some examples will have all four types of files to choose from, some fewer than four.

The CD includes:

- Web-based self-quiz software that tests understanding of each chapter and provides explanations of right and wrong answers, plus browser software and a Web connection package from AT&T Worldnet™, if Internet access is not already available.
- The evaluation version of MicroSim PSPICE® for Windows®-based computers, and electronic copies of all the SPICE netlists printed in this book.
- The evaluation version of the Student Edition of Electronics Workbench® for Windows-based computers, which will load a set of files keyed to the book and allow students to work their own problems.
- MATLAB and MATHCAD files that work and extend specific examples in the book.

The contents of the CD provide a broad range of electronic ancillary support from which the instructor and the student can pick and choose to best support the course and the book.

Acknowledgments

At PWS Publishing, I would like to single out William Barter, who showed interest, faith, and commitment to the approach to circuit analysis I have presented here. It is not easy for a person trained in one field to understand the technical intricacies of another specialization. Bill did, and his continued faith and moral support were invaluable in the completion of this text. As everyone who has written a text knows, it is a long and arduous task and nerves begin to become a bit frayed toward the end of the process. Bill always provided a cool-headed, sane approach to each problem as it arose, and his solutions were always rational and considered. Nathan Wilbur provided quite a bit of assistance in "putting it all together": articulating what the book is all about. He has aided me in several ways with a very perceptive and analytical evaluation of "how to say things" at just the right moment.

Leslie Bondaryk is the "web guru" who took on the onerous task of putting some of the text material on line. Yet she did even more. She has been fiendishly clever at thinking up ways of presenting somewhat abstract concepts in a design-oriented manner. She also made several valuable suggestions about the text presentation itself.

Andrea Goldman has provided a lot of behind the scenes support, taking care of details in such a manner that they were invisible to me (one of the most meaningful kinds of support, but one that too often goes unacknowledged). Helen Walden provided very competent support with the editing through many vagaries in the process, such as the sudden UPS workers strike that impeded the flow of manuscript for a time. She, too, was a cool head to whom I turned several times for that type of assistance that is so valuable, yet is "not in the job description." Torrey Lee Adams did a superb job of line editing, and I

learned several things about tight, clean writing from her. She helped by clarifying my writing in a number of ways.

At the top of the list of those who provided technical assistance go my students over the years, who have been the best critics of this work. Their questions, suggestions, error corrections, and enthusiastic response to the methods contained in this text were invaluable. Without them, the book would simply not have been written. There is one student, however, whom I would like to single out for a special thank you: George Wong. George studied circuit analysis with me while acquiring the background to make the transition from his undergraduate field of chemical engineering to the graduate program at San Jose State University. Not only was George an exemplary student, he was (and is) a very hard-working and precise person. His support has been invaluable in pointing out errors in the manuscript and in writing the solution manual that accompanies the text.

Among my San Jose State University colleagues, several have provided support in one manner or another. Gene Moriarty taught from the manuscript and provided valuable suggestions while it was being developed, as did Patricia Johnson and Richard Duda. Michael O'Flynn showed me an interesting derivation of the Fourier transform of the unit step function that led to the entire approach for defining the Fourier transform in Chapter 14. Jack Kurzweil pointed out the fact that the Fourier series can be treated as a special topic in Fourier transform theory. I learned the "quick method" of doing linearized Bode gain plots from Evan Moustakas, though the extension of the technique to phase plots is my own. I also would like to say thanks to Moustakas for sharing several of his pedagogical devices with me when I was a neophyte instructor. Ray Chen, the department chair, provided support by allowing me to use the text in class as it was being developed and by providing a somewhat lightened teaching load in the last stages of the writing.

As for colleagues not affiliated with San Jose State, I would like to select several who contributed in significant ways, in one manner or another, to the development of *Linear Circuit Analysis*. Armen Zemanian at New York State University at Stony Brook has provided a mentoring type of support over the years. He is a person whom I admire and respect for his truly significant accomplishments in the field of circuit theory and for his willingness to support younger colleagues. Gary Ford, at the University of California at Davis, a fine teacher and circuit theorist, helped greatly in several ways. As a personal favor, he reviewed an early version of a manuscript for a paper upon which the Heaviside operator technique is based (as did Zemanian), and made valuable comments that led to significant improvements, directly in the paper and more indirectly in this book. Of special note is his contribution to my understanding of the relationship between mathematical and physical operations, as exemplified in the treatment of complex variables in Chapter 8. This treatment was also motivated to a large extent by fairly recent research results in filter design published by Sanjit Mitra at U.C. Santa Barbara, P. P. Vaidyanathan at Cal Tech, Adel Sedra at the University of Toronto, and others. Over the years, I have considered the work of these people to be inspiring in molding my own thinking on the subject.

P. M. Lin of Purdue also reviewed the operator paper mentioned above and offered substantive comments. Furthermore, the method used in this text for presenting the reciprocity of mutual inductance is due to Dr. Lin. I learned it as an associate editor for the *IEEE Transactions on Circuits and Systems,* when I was charged with the responsibility of seeking out good tutorial papers for that journal's Circuits and Systems Expositions (CASE) section. Dr. Lin contributed a paper on the reciprocity of mutual inductance during that time, and I benefited greatly by corresponding with him on the subject. Much the same can be said of Wai-Kai Chen, whose texts and papers have influenced me over the years and who also offered valuable suggestions leading to the improvement of my earlier paper on circuit analysis using Heaviside operators.

Ron Rohrer is responsible for stimulating me to think about the relation between two-sided and one-sided waveforms and the ideas of forced responses and steady state through a couple of what seemed at the time to be passing comments about his classroom approach to these subjects. These comments were made to me at a professional meeting a number of years ago and proved to be quite fundamental, contributing greatly to the frequency domain analysis used in *Linear Circuit Analysis.* I have also been greatly influenced by Dr. Rohrer's more advanced circuits texts, as well as the aforementioned one of Dr. Vitold Belevitch.

In a broader manner, I have benefited from discussions with many other colleagues. Ken Jenkins at the University of Illinois provided several opportunities for professional growth in the discipline of circuit theory through the IEEE Circuits and Systems Society, and his oral presentations of technical papers influenced by own style of speaking and writing. Terry Cotter at the University of New Bruswick at Saint John inspired me to think in a fundamental way about the physical significance of complex power. Mohammed Ismael at Ohio State, Igor Filanovsky at the University of Edmonton in Alberta, Peter Aronheim at the University of Louisville, and William Stephenson at Virginia Tech influenced my thinking about active networks that is presented in these pages.

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