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DESIGN OF ANALOG INTEGRATED CIRCUITS AND SYSTEMS

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To our families
Mary Ellen, John, Chris, and Brian
Hadewych, Katrien, Sara, and Marjan

PREFACE

In the short span of twenty five years, the field of analog integrated circuits and systems has developed and matured. During this same period, much has been made of the competition between analog and digital system design strategies. Advances in digital VLSI has enabled microprocessors and digital-signal processors to assume roles largely filled in the past by analog systems. However, there are three facts that render analog integrated circuits and systems increasingly important. First, the natural world is analog. Thus, analog systems are needed in information acquisition systems in order to prepare analog information for conversion to digital format. Second, there remain many important applications that are best addressed by mixed analog/digital VLSI systems. That is, analog and digital VLSI circuits coexist on the same die. Third, demanding digital systems can exhibit analog circuit qualities. Thus, a good grasp of analog IC design techniques is a valuable asset in the design and debugging of digital systems. The advances in both analog and digital VLSI has profoundly changed the way systems are partitioned to optimize integration and cost.

Much of the analog design during the 1960s and 1970s was done in bipolar and hybrid technologies. During this time, the operational amplifier emerged as an important subsystem. During subsequent years, the operational amplifier has been optimized and scaled to the degree that it is now considered a common component, like a resistor or capacitor. The 1980s was an era of rapid evolution of MOS analog integrated circuits, in particular CMOS. During the 1990s, we have seen the BICMOS technology (incorporating both bipolar and CMOS devices on the same die) emerge as a serious contender to the original technologies. Although somewhat more expensive to fabricate (e.g., more mask levels) than CMOS, BICMOS allows the designer to use both bipolar and MOS devices to their best advantage. At the same time, we have seen a proliferation of mixed analog/digital VLSI integrated circuits realized in state-of-the-art digital CMOS technologies to optimize cost and power dissipation in consumer products, many of which are pocket size and battery powered. For very high performance applications, BICMOS offers the opportunity to mix analog circuits on the same die with high-speed ECL digital circuits and dense CMOS logic.

It has become increasingly important for analog circuit designers to have a thorough appreciation of the similarities and differences between MOS and bipolar devices, and to be able to design with either, where appropriate. The same argument can be made for sampled-data and continuous-time design techniques. Thus, in this book, we combine the consideration of CMOS and bipolar circuits into a unified treatment. We also include combined CMOS-bipolar circuit realizations made possible by BICMOS technology. The text progresses smoothly from MOS and bipolar device modeling, to simple one- and two-transistor building block circuits (e.g., amplifiers, active loads, and sources). We then follow with a thorough treatment of the design of operational and transconductance amplifiers. The final two chapters present a unified coverage of sample-data and continuous-time signal processing systems. Earlier in the text, we thoroughly cover the concepts of feedback and sensitivity. These important topics, along with noise, nonlinear distortion, and power supply rejection are integrated, as needed, throughout the text.

The design of analog circuits relies heavily on insight gained from hand calculations based on first-order models. However, many important details of circuit behavior, such as precise gain, DC offsets, distortion, and noise, depend on second-order device characteristics that cannot be included in hand calculations. We use computer analysis the way it is most commonly employed in the engineering design process: as a tool to verify detailed circuit behavior beyond the scope of hand analysis. The circuit simulator called SPICE is the standard CAD tool for verifying integrated circuit performance. SPICE is available in a variety of forms on UNIX-based workstations and all popular PC platforms. With these thoughts in mind, we focus much of the text on the development of design intuition through hand calculations. Extensive use of SPICE is included thoughout the text, particularly as part of examples in the problem sets. The problem sets also include several open-ended design problems that expose the reader to practical situations.

Both authors have had extensive industrial experience in integrated-circuit (IC) design, as well as in the teaching of academic courses on this subject. The choice of the material covered in the body of the text and the problem sets is a reflection of our collective experience. We believe it to be a valuable resource for both IC designers and users. An understanding of the IC structure is extremely useful in evaluating the relative desirability of different designs. In addition, the IC user is in a much better position to interpret a manufacturer's data if he or she has a working knowledge of the internal operation of the integrated circuit in question.

This text was written to be used both as a text for students and as a reference book for practicing engineers. For class use, there are numerous worked problems in each chapter; the problem sets at the end of each chapter illustrate the practical applications of the material in the text. The contents of this book originated largely for the purpose of serving two courses on analog integrated circuit design offered at the University of Pennsylvania and the Katholieke Universiteit Leuven. The first of these is a senior level elective and the second is a first year graduate course. The book is structured so that it can be used as the basic text for such a two-course sequence. An outline of each chapter will follow shortly, together with suggestions for material to be covered in each course. We assume that each course consists of three hours of lecture per week over a 15-week semester. The users of this text are assumed to have a working knowledge of Laplace transforms and frequency-domain circuit analysis. We also assume that the readers have had an introductory course in electronics, such as that based on the text *Microelectronic Circuits* by A. Sedra and K. C. Smith. Thus, we expect readers to be familiar with the principles of transistor operation and with the functioning of simple analog circuits. We also expect that readers have an introductory knowledge of probability and statistics. We take advantage of the fact that an increasing number of students are exposed to sampled-data systems and the z-transform in their undergraduate curriculum. For those readers who have not been exposed to this material, and for those who wish to revitalize this knowledge, an introduction to sampled-data signals and systems is included in Appendix 7-1 at the end of Chapter 7.

The outline of the text is as follows:

Chapters 1 and 2 contain summaries of MOS and bipolar transistor models, respectively. This material is quite important in IC design because there is significant interaction between circuit and device design, as will be seen in later chapters. The components that are most crucial in achieving an accurate SPICE simulation are the device models. Thus, a thorough understanding of the influence of device fabrication on device characteristics and their models is essential. Both chapters in their entirety are required reading for both the undergraduate and graduate courses. We suggest spending one to two weeks on selected topics from these chapters, with the choice of topics depending on the background of the students.

Chapter 3 introduces the reader to the important concepts of feedback and sensitivity. Also included are the effects of feedback on transient response of second- and third-order systems. Some of this material will be review for some students, particularly at the graduate level. Particularly novel in this chapter is the inclusion of two powerful tools for designing feedback circuits, namely, Blackman's impedance relation and the asymptotic gain relation. In the undergraduate course, this chapter should be covered in full. It will require no more than two weeks to cover. For the graduate course, selected topics can be treated in class and the balance of the chapter as home reading. One week is allowed for this chapter in the graduate course.

Chapter 4 involves the use of transistors to construct elementary amplifier stages, buffers, impedance converter, active loads, and current sources. AC, DC, and transient performances are considered. Capacitances (both intentional and parasitic) give rise to poles and zeros that modify the input, output, and transfer relationships versus frequency. In all sections, the parallel between MOS and bipolar transistor stages is maintained; and the differences are highlighted. The configurations in this chapter represent the basic building blocks of modern analog IC design. Thus, in both courses this material should be covered in full with the exception of the appendices. A thorough treatment of this chapter will require three weeks. We recommend coverage of the full chapter for the undergraduate course and selected topics for the graduate course. For the graduate course, coverage is reduced to two weeks.

Chapter 5 is concerned with the modeling of operational and transconductance amplifier-based circuits from a behavioral point of view. A strong behavioral understanding is a prerequisite to undertaking the transistor level design of these amplifiers and/or the synthesis of higher level circuits that use them as components. The designer can greatly simplify the analysis and design of complex analog systems by using models for the amplifiers derived from behavioral descriptions rather than circuit schematics. Behavioral models developed in this chapter are used extensively in the analysis and design of analog signal processing systems in Chapters 7 and 8. Moreover, they are used in Chapter 6 to map detailed specifications to the attributes of transistor level circuit schematics. We recommend full coverage of this chapter in both courses, requiring two weeks.

Chapter 6 considers the transistor level analysis and design of several operational (op amp) and transconductance (OTA) amplifier schemes. They are developed by first considering the differential amplifier with active load, the simplest complete OTA. Succeeding schemes for CMOS, bipolar, and BICMOS, are developed with this basic OTA as a kernel. Fully differential or balanced schemes are also considered. Design plans are applied to all schemes, paying considerable attention to symmetry and matching, and also to other second-order effects (e.g., transient response, noise, nonlinearities, power supply rejection, offsets, common mode rejection, temperature effects), leading to a full set of specifications. Several design examples are worked in detail and important design tradeoffs are discussed. A thorough treatment of this chapter will require three weeks. We recommend coverage of the full chapter for both the undergraduate and graduate courses.

Chapter 7 is devoted to reviewing the fundamentals of linear active filtering in the continuous-time and sampled-data domains. For those readers who need to refresh their understanding of sampled-data systems, and z-transform, a brief review of these subjects is provided in Appendix 7-1. The fundamental schemes for integrated analog filters are introduced. Various performance requirements and methods for synthesizing efficient numerical transfer functions are considered. Models developed in Chapter 3 are used to estimate sensitivity and yield. A hybrid of discrete-time and analog circuit concepts are developed to facilitate the symbolic analysis and design of switched-capacitor circuits. A thorough treatment of this chapter requires three weeks. If Appendix 7-1 is reviewed in class, it can be adequately covered in two lectures. For the undergraduate course we recommend emphasizing continuous-time filters, providing an introduction to switched-capacitor filters. This involves all of Sections 7-1, 7-2, and 7-4, and parts of Sections 7-3, 7-5, and 7-6. This entire chapter is to be covered in the graduate course.

Chapter 8 builds on the materials in Chapters 5–7 to design and implement practical continuous-time and sampled-data integrated active filters. We consider concepts, circuit designs, circuit schematics, and design lore that have been found to result in robust integrated filters. Continuous-time and sampled-data realizations are considered with equivalent emphasis. Design and implementation is based on modular structures, where op amps, OTAs, and the passive structures are the building blocks. All schemes are analyzed, paying considerable attention to parasitics and matching, and also to other second-order effects (e.g., transient response, noise, nonlinearities, power supply rejection, and DC offsets). A thorough treatment of this chapter requires three weeks. There remains one week in the undergraduate course to cover selected sections. We recommend the coverage of Sections 8-1–8-3. The entire chapter is to be covered in the graduate course.

This book was conceived during W. Sansen's sabbatical leave with K. Laker at the University of Pennsylvania. The book was further developed during K. Laker's subsequent sabbatical leave at the Katholieke Universiteit Leuven. The funding for both sabbatical leaves were provided by the Penn-Leuven Faculty Exchange program. We are indeed grateful for this support. We wish to thank our students, colleagues, and the following reviewers for their careful evaluation of this book and their thoughtful comments: Stanley G. Burns, Iowa State University; L. Richard Carley, Carnegie Mellon University; Sherif Embabi, Texas A & M University; Sergio Franco, San Francisco State University; Edwin Greeneich, Arizona State University; Frank H. Hielscher, Lehigh University; Andrew L. Robinson, University of Michigan; Mani Soma, University of Washington; Bang-Sup Song, University of Illinois at Urbana–Champaign; and Gary Tuttle, Iowa State University. In particular, we wish to acknowledge the helpful suggestions from Professor Jan Van der Spiegel, University of Pennsylvania; Dr. T. R. Viswanathan, AT&T Microelectronics, Professor Michel Steyaert, Katholieke Universiteit Leuven, and Mr. A. Ganesan, Crystal Semiconductor.

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