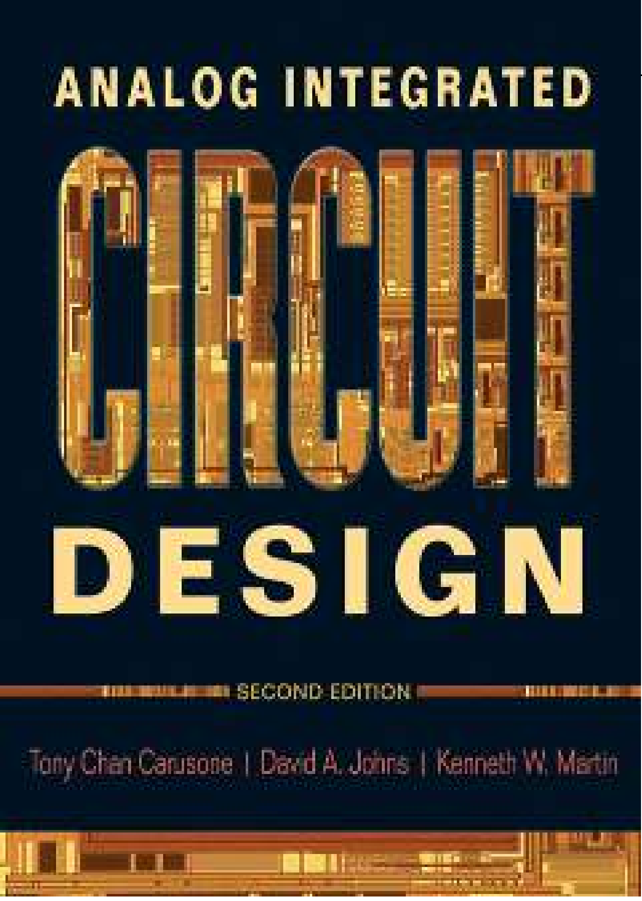
ANALOG INTEGRATED
CIRCUIT
DESIGN
SECOND EDITION
Tony Chan Carusone | David A. Johns | Kenneth W. Martin

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To Soo, Brayden, Teague, and Senna
To Cecilia, Christopher, Timothy, and Victoria
To Elisabeth and Jeremy

Preface

It has long been predicted that there would soon be little need for analog circuitry because the world increasingly relies on digital signals, yet the need for good analog circuit design remains strong. Many applications have indeed replaced analog circuitry with their digital counterparts (such as digital audio). However, when digitizing physical signals, analog-to-digital and digital-to-analog converters are always needed, together with their associated anti-aliasing and reconstruction filters. In addition, new applications continue to appear; their requirements demand the use of high-performance analog front ends, such as digital communication over wireline and wireless channels and microsensor interfaces. Also, as integrated circuits integrate more functionality, it is much more likely that at least some portion of a modern integrated circuit will include analog circuitry to interface to the real world. Moreover, the continued scaling of digital circuits has led to the emergence of new problems that require analog solutions, such as on-chip power management and the generation of stable clock signals. Although it may constitute only a small portion of total chip area, analog circuitry is often the limiting factor on overall system performance and the most difficult part of the IC to design. As a result, a strong industrial need for analog circuit designers continues. The purpose of this book is to help develop excellent analog circuit designers by presenting a concise treatment of the wide array of knowledge required by an integrated circuit designer.

This book strives to quash the notion that the design and test of high-performance analog circuits are "mystical arts." Whereas digital design is relatively systematic, analog design appears to be much more based upon intuition and experience. Analog testing may sometimes seem to depend more upon the time of day and phase of the moon than on concrete electrical properties. But these thoughts about analog circuits usually occur when one is not familiar with the many fundamentals required to create high-performance analog circuits. This book helps to take the mystery out of analog integrated circuit design. Although many circuits and techniques are described, the most important design principles are emphasized throughout this book. Physical and intuitive explanations are given, and although mathematical quantitative analyses of many circuits have necessarily been presented, one must not miss seeing the forest for the trees. In other words, this book attempts to present the critical underlying concepts without becoming entangled in tedious and overcomplicated circuit analyses.

NEW TO THIS EDITION

This, the second edition of Analog Integrated Circuit Design, has new material to make it more accessible to beginners in the field while retaining the depth, detail, and intuitive approach that made the first edition a favorite reference among experienced designers. Two new chapters have been added early in the text: Chapter 4, dedicated to the frequency response of analog integrated circuits, provides a review of frequency-domain analysis and single-stage amplifier response; Chapter 5 covers the basic theory of feedback amplifiers. The conventional categorization and dissection of feedback amplifiers according to their topology is by and large forgone in favor of an intuitive, practical, yet analytical approach that is based on the practices of experienced analog designers. These new chapters make the second edition well-suited to the teaching of analog integrated circuit design at both the undergraduate and graduate levels, while still allowing it to serve as a comprehensive reference for practicing engineers.

The first edition of Analog Integrated Circuit Design was written roughly 15 years before the second, and the field changed considerably in the intervening years necessitating significant updates to reflect advances in technology and engineering practice. For example, material on CMOS integrated circuit device modeling, processing, and layout in Chapters 1 and 2 has been updated and expanded to cover effects that are of tremendous importance to analog designers using modern fabrication technologies. New and expanded topics include modeling MOS subthreshold operation and mobility degradation in Chapter 1, and proximity effects and mismatch both covered under the subheading "Variability" in Chapter 2. Also in Chapter 1, the increasingly important role of simulation in the early phases of analog design is reflected by relating MOS parameters to the results of practical simulations. Simulation examples have been added throughout the text, particularly in the early chapters. Circuits and architectures whose fundamental importance have emerged over the past decade have been added such as voltage regulators (in Chapter 7) and the 1.5-bit-per-stage pipelined A/D converter (in Chapter 17). New circuit topologies specifically suited to low-voltage operation are presented, such as a low-voltage bandgap reference circuit in Chapter 7. Nonlinearity and dynamic range are now presented in Chapter 9 alongside noise, highlighting their fundamental interrelationship. New study problems have been added throughout the text and numerical examples have been updated to reflect the realities of modern fabrication technologies.

This edition has also been updated to accommodate today's varying pedagogical approaches toward the teaching of bipolar devices and circuits. Material on bipolar devices and circuits, which was scattered over several chapters of the first edition, has been combined into Chapter 8 of this edition. The reorganization permits undergraduate-level instructors and readers to either incorporate or omit the material at their discretion. In the later chapters, readers are assumed to have experience with analog design, hence bipolar and BiCMOS circuits are presented alongside CMOS circuits, as in the first edition.

Finally, Chapter 19 on phase-locked loops (PLLs) has been rewritten. When the first edition was released, it was one of the first analog circuit texts to elucidate the design of integrated circuit PLLs. Today, fully-integrated PLLs have become a basic building block of both analog and mostly-digital integrated circuits. As such, the material has become standard fare at the graduate level, and increasingly at the undergraduate level too. Chapter 19 now provides a thorough treatment of jitter and phase noise, major performance metrics in the design of modern PLLs and clocked systems.

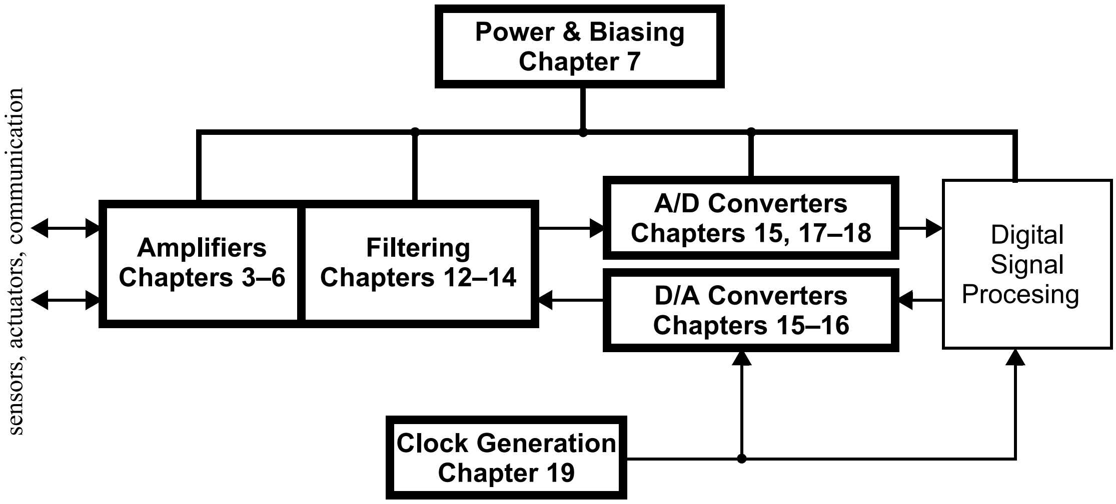
INTENDED AUDIENCE

This book is intended for use as a senior-undergraduate and graduate-level textbook, and as a reference for practicing engineers. To appreciate the material in this book, it is expected that the reader has had at least one basic introductory course in electronics. Specifically, the reader should be familiar with the concept of small-signal analysis and have been exposed to basic transistor circuits. In addition, the reader should be have been exposed to Fourier and Laplace transforms. Some prior knowledge of discrete-time signal processing is important for the later chapters. Although all of these topics are reviewed, background in these areas will benefit the reader significantly.

The chapters of this book have intentionally been made mostly independent so that some chapters can be covered while others are skipped. Also, it has been found to be very easy to change the order of presentation. For example, if readers have a good modelling background they might skip Chapter 1, and if their discrete-time knowledge is good Chapter 13 might he assigned only as review. We believe that such flexibility is essential in presenting textbooks for the later years of study.

The material in this book can be used for a few courses. A second undergraduate course in electronics typically has frequency response and feedback, as its major topics. For such a course, Chapters 1, 3, 4 and 5 may be assigned. Some advanced modeling from Chapter 1 may be omitted and replaced with selected topics from Chapters 2 and 6 at the instructor's discretion. A senior-level undergraduate course in analog integrated circuits assigns Chapters 1, 2, 6, and 7, with Chapters 3–5 serving as a useful reference for those students requiring extra review. Chapter 8 may be included in any course that covers bipolar processing and devices.

A senior undergraduate or entry-level graduate course on analog signal processing may use Chapters 9–14. A graduate-level course on data converters will focus upon Chapters 15–18, drawing upon the earlier chapters as



needed for supplementary material. Finally, Chapter 19 may be used for a graduate level course on phase locked loops. Naturally there is considerable variability in the specific readings assigned by different instructors, particularly at the graduate level. This variability is recognized in the basic organization of the book.

A secondary audience for this book includes recently graduated electrical engineers who wish to rapidly increase their knowledge of modern analog circuit design techniques. In fact, much of the material covered in this text was originally taught and refined over many years in popular short courses offered to working engineers who realized the importance of upgrading their knowledge in analog circuit design. For this audience, we have put effort into highlighting the most important considerations when designing the various circuits. We have also tried to include modern, well-designed examples and references to primary sources for further study.

TEXT OUTLINE

Analog integrated circuits are critical blocks that permeate complex electronic systems. Analog circuits inevitably arise whenever those systems must interact with the analog world of sensors or actuators (including antennas, cameras, microphones, speakers, displays, lighting, motors, and many others), and when they must communicate using anything but the most rudimentary digital signals. A typical system is illustrated in the figure. The blocks covered in some detail in this text are highlighted, and the corresponding chapters referenced. Chapters describing the design of amplifiers, and all chapters not explicitly referenced in the figure, are foundational and relevant to the implementation of many analog and mixed-signal systems. The table of contents provides a catalog of the book's main topics. What follows here is a very brief summary of each chapter.

In Chapter 1, the basic physical behavior and modelling of diodes, MOS transistors, and integrated circuit capacitors and resistors are covered. Here, many of the modelling equations are derived to give the reader some appreciation of model parameters and how they are affected by processes parameters. Diode and MOSFET models are summarized in a table format for quick reference.

In Chapter 2, issues associated with the manufacturing of an integrated circuit are discussed. Emphasis is placed on CMOS fabrication. In addition to the provided background, issues that are of particular importance to analog designers are emphasized, such as variability (including random mismatch) layout rules and best practices.

Fundamental building blocks of analog integrated circuits are discussed in Chapter–3, specifically, MOS current mirrors and single-stage amplifiers, concluding with the basic MOS differential pair. A point to note here is that only active-load amplifiers are considered since these are prevalent in integrated circuits.

Chapter 4 provides an introductory view of the frequency response of electronic circuits. It begins with fundamental material on frequency response, establishing definitions and notation for the following chapters. Then, the frequency response of elementary CMOS analog building blocks is presented. Along the way, fundamental topics are presented including the Miller effect and the method of zero-value time-constants.

Feedback amplifiers are introduced in Chapter 5. Loop gain and phase margin are defined. Basic concepts are illustrated using generic analyses of first- and second-order feedback systems. At the end of the chapter, the analysis is applied to common CMOS feedback circuits.

In Chapter 6, the fundamental principles of basic opamp design are presented. To illustrate many of these principles, the design of a classic two-stage CMOS opamp is first thoroughly discussed. Proper biasing and device sizing strategies are covered. Compensation is introduced and a systematic procedure for compensation is described. Then, advanced current-mirror approaches are discussed, followed by two opamps that make use of them: the folded-cascode and current mirror opamps. Finally, fully differential opamps are presented, as they are used in many modern industrial applications where high speed and low noise are important considerations.

Biasing, reference, and regulators are presented in Chapter 7. Any reader that wishes to design a real and complete opamp circuit should be aware of the attendant issues covered here. The later sections on bandgap references and voltage regulators may not be essential to all readers.

Chapter 8 provides a comprehensive summary of bipolar devices and circuits. It includes the basics of device modeling, fabrication, and fundamental circuit blocks such as current mirrors and gain stages. The reader may wish to read sections of this chapter alongside the corresponding material for MOS transistors presented in Chapters 1–7.

Noise analysis and modelling and linearity are discussed in Chapter 9. Here, we assume the reader has not previously been exposed to random-signal analysis, and thus basic concepts in analyzing random signals are first presented. Noise models are then presented for basic circuit elements. A variety of circuits are analyzed from a noise perspective giving the reader some experience in noise analysis. Finally, the concept of dynamic range is introduced as a fundamental specification of most any analog circuit, and the basic measures of linearity are defined.

In Chapter 7, comparator design is discussed. Comparators are perhaps the second most common analog building block after opamps. Here, the practical limitations of comparators are described as well as circuit techniques to improve performance. In addition, examples of modern high-speed comparators are presented.

In Chapter 11, some additional analog building blocks are covered. Specifically, sample-and-hold circuits and translinear gain and multiplier circuits are presented. By the end of this chapter, all the main analog building blocks have been covered (with the possible exception of voltage-controlled oscillators) and the remaining material in the text deals with more system-level analog considerations.

Continuous-time filters are the focus of Chapter 12. After a brief introduction to first- and second-order filters, transconductance-C filters are described. CMOS, bipolar, and BiCMOS approaches are covered. Active-RC filters are then presented, followed by some tuning approaches. Finally, a brief introduction to complex analog signal processing and complex filters is included.

The basics of discrete-time signals and filters are presented in Chapter 13. This material is essential for understanding the operation of many analog circuits such as switched-capacitor filters and oversampling converters. The approach taken here is to show the close relationship between the Z-transform and the Laplace transform, thereby building on the reader's experience in the continuous-time domain.

In Chapter 14, the basics of switched-capacitor circuits are described. Switched-capacitor techniques are a common approach for realizing integrated filters due to their high degree of accuracy and linearity. The chapter concludes with a description of other switched-capacitor circuits. such as gain stages, modulators, and voltage-controlled oscillators.

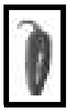
In Chapter 15, the fundamentals of data converters are presented. Ideal converters and the properties of quantization noise are discussed first. Signed codes are then presented, and the chapter concludes with a discussion of performance limitations and metrics.

Popular Nyquist-rate D/A architectures are discussed in Chapter 16 and various approaches for realizing Nyquist-rate A/D converters are described in Chapter 17. The importance of data converters cannot be overemphasized in today's largely digital world, and these two chapters discuss the main advantages and design issues of many modern approaches.

Oversampling conveners are presented separately in Chapter 18 due to the large amount of signalprocessing concepts needed to properly describe these converters. Here, digital issues (such as decimation filters) are also presented since good overall system knowledge is needed to properly design these types of converters. In addition, practical issues and advanced approaches (such as the use of bandpass and multibit converters) are also discussed. This chapter concludes with a third-order A/D converter example.

Finally, the text concludes with phase-locked loops (PLLs) in Chapter 19. The chapter first provides a big-picture overview of PLLs. A more rigorous treatment follows, including small-signal analysis and noise analysis in both the time domain (jitter) and frequency domain (phase noise). Performance metrics and design procedures are included.

USING THE BOOK AND WEBSITE



SPICE simulation examples are an important feature of the book. Passages annotated with the boxed icon shown here indicate that a SPICE simulation may be performed either as an essential part of the problem, or to corroborate the results of a hand analysis. Many of the problems and examples in this book rely upon the fictitious CMOS process technologies whose parameters are summarized in Table 1.5. SPICE model files corresponding to each of these fictitious technologies are provided on the companion website, **www.analogicdesign.com**. Also there are many netlists that may be used for the simulations. The results they provide should roughly corroborate hand analyses performed using the parameters in Table 1.5. However, simulation results *never* provide precise agreement. In fact, simulated results may differ from the results of a hand analysis by as much as 50%! This is a reality of analog design, and the SPICE examples in this book are no exception. This is, of itself, a valuable lesson to the student of analog design. It illustrates, through practice, those tasks to which hand analysis and simulation are best suited.

End-of-chapter problems are organized by the subsection to which they pertain. For example, if one wishes to practice only those problems pertaining to current mirror opamps, one may proceed directly to Section 6.11.5.

Key points throughout the text are emphasized using highlighted boxes in the margins, as shown here. These key points are collected and listed at the end of each chapter.

***Key Point:** Key points throughout the text are emphasized using separate highlighted boxes in the margins. These key points are collected and listed at the end of each chapter as a study aid.*

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