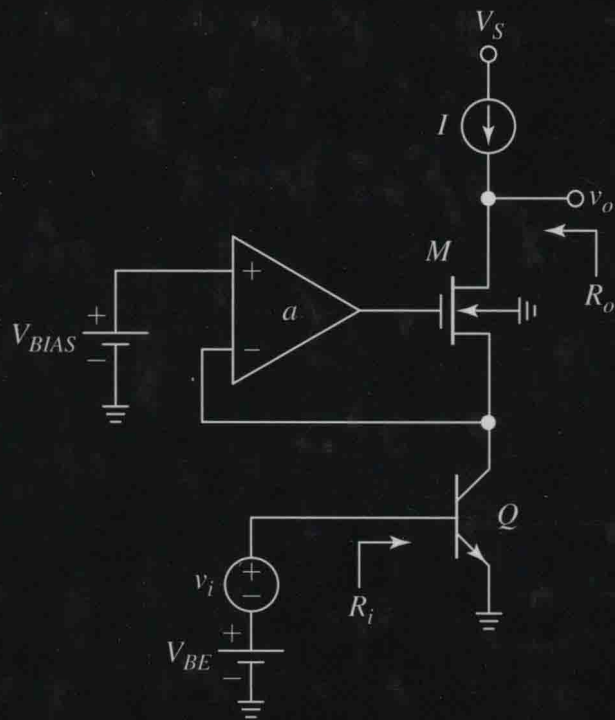


Analog Circuit Design

Discrete & Integrated



Sergio Franco



ANALOG CIRCUIT DESIGN

DISCRETE AND INTEGRATED

Sergio Franco

San Francisco State University

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ANALOG CIRCUIT DESIGN: DISCRETE AND INTEGRATED

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ANALOG CIRCUIT DESIGN

DISCRETE AND INTEGRATED

Dedication

In Memory of My Parents

Luigia Braidotti and Luigi Franco

Preface

This textbook is intended for EE majors envisioning industrial careers in analog electronics. Analog integrated-circuit designers, product/process/reliability engineers, test/test-development engineers, and analog applications/marketing/customer-support engineers are always in great demand. The book is the result of my teaching experience at San Francisco State University, where over the years I have contributed to the formation of hundreds of students now gainfully employed in Silicon Valley in a wide range of analog positions. Here are three important features of this book:

- Both *bipolar* and *CMOS* technologies are covered. Even though digital electronics is dominated by CMOS technology, analog electronics relies on both CMOS and bipolar, the latter being the technology of choice in high-quality analog circuits as well as a fundamental part of BiCMOS technology.
- Both *discrete* and *integrated* designs are covered. Though nowadays the ultimate form of an analog system is likely to be of the integrated-circuit type, testing and applications often require ancillary functions such as conditioning and interfacing that are best realized with ad-hoc discrete designs. (Anyone familiar with the work by recognized leaders in analog applications/testing/instrumentation like Jim Williams and Robert Pease will agree to this.) In this respect, BJTs are available in a wide selection of off-the-shelf discrete types to serve a variety of needs, including practical experimentation in the lab. Moreover, for pedagogical reasons it is convenient to cover simple discrete circuits before tackling the more complex integrated circuits.
- *Semiconductor theory* is presented in sufficient depth to reflect the daily needs of a practicing engineer in industry. Every analog function is inextricably rooted on a physical phenomenon, so analog engineers, particularly IC designers and product/process/reliability engineers, need to be conversant with the physics of semiconductors in order to function optimally.

BOOK ORGANIZATION

The book is organized into two parts:

- The first part covers (1) *Diodes*, (2) *BJTs*, and (3) *MOSFETs*; as such, it is suited for a *first course in electronics*, typically at the junior level. The material is sequenced according to the technological evolution of electronics. However, the instructor who wishes to change the order of coverage of BJTs and MOSFETs can easily do so, as the two chapters are autonomous. Regardless of the order, the last chapter in the sequence can be covered much faster than the previous one as the student has already faced the challenges of dc biasing and large/small signal modeling.

- The second part covers (4) *Analog IC Building Blocks*, (5) *Representative Analog ICs*, (6) *Frequency and Time Responses*, and (7) *Negative Feedback, Stability, and Noise*. This part is suited for a *junior/graduate-level course* in analog IC analysis and design. In this part, BJTs and MOSFETs are mostly covered *side by side* so as to offer a unified treatment emphasizing similarities while recognizing inherent differences.

Each chapter provides a fairly comprehensive coverage of its title subject, so chapters are of necessity long (>100 pages each). The overall amount of material exceeds that of a typical two-semester or four-quarter course sequence, so the instructor has considerable leeway in material selection. Also, the author feels that the student needs to fully master low-frequency circuits before proceeding to the more challenging frequency and time responses of Chapter 6. But, the instructor can modify the coverage by skipping suitable topics from Part I in favor of selected topics from Chapter 6.

As mentioned, the first part focuses on basic transistor circuits emphasizing the more traditional *discrete design* approach. Pedagogically, it makes sense to study single-transistor circuits before progressing to multi-transistor systems—so much the better if this part is accompanied by a lab, where it is easier to investigate simpler circuits. In fact, at this level, a lab (complete with smoke!) is likely to offer a far more valuable learning environment than a computer-simulated one. A notorious drawback of discrete circuits is the need for coupling/bypassing capacitors, which introduce an element of additional distraction as it takes time for the student to develop full confidence with these capacitance functions. Cognizant of this, I have tried to demystify capacitors via detailed visual examples (see Fig. 2.55, p. 181, and Fig. 3.60, p. 302).

Following discrete circuits, the book progresses to *integrated circuits*. The integrated and discrete approaches are contrasted in Section 4.1; also, an intuitive borderline between the two is discussed in Exercise 4.3, p. 357. The second part progresses in complexity as well as sophistication from building blocks, to representative analog ICs, to IC dynamics, and finally to IC operation in negative-feedback, along with stability considerations, frequency compensation, and noise. This part is intended for IC designers but also for all other categories of engineers involved in fabrication, test, and applications. Application engineers, by far the largest group, need a working familiarity both with the technology (in order to make educated selections) and with the IC's inner functioning (in order to optimize its application). The book's aim is to promote a balance between the ability to *design on chip* and the ability to *design on board*.

The book website features a solutions manual and PowerPoint lecture slides for instructors as well as a list of helpful web links and errata. The author appreciates being notified of any possible errata.

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MOTIVATION

After having experimented with a number of other textbooks, I decided to write my own in response to a number of student concerns and also to implement my own ideas on how to better serve the needs of our graduates, who generally pursue careers in industry. Following are the most common student concerns:

- *Need to see lots of examples, especially of the type practicing engineers face daily.* I have painstakingly thought out each in-text example and end-of-chapter problem to serve two broad needs: to help the student develop a *feel* for the orders of magnitude of the quantities under study (see, for instance, Example 1.8, p. 42), and to deepen student *understanding* by following a circuit's evolution through different states or through increasing levels of complexity (see Figs. 1.18–20, pp. 16–17). In this respect, I made a concerted effort to develop a *systematic problem-solving methodology* emphasizing *thinking* and *physical intuition* as opposed to rote calculations. For it is in physical understanding, not in mathematical manipulations or computer simulations, that is rooted the design creativity the student will be called to exercise on the job. The book contains valuable rules-of-thumb working engineers use daily (see pp. 50, 52–55). Whenever possible, the student is reminded to use intuition and physical insight to anticipate what to *expect* from calculations or computer simulations, and to *check* results against physical substance (for physical insight see Example 6.5, p. 583, and Fig. 793, p. 787).
- *Incorporate SPICE simulation within the text.* SPICE has been integrated throughout the text both as a *pedagogical aid* to confer more immediacy to a new concept (see Fig. 4.66, p. 424), and as a *validation tool* for hand calculations. If unreasonable discrepancy is found between calculations and simulations, the student is challenged to account for possible causes (see Example 5.2, p. 490). Finally, SPICE is used to bring out nuances that would be too complex for hand calculations (see Example 6.11, p. 602). Nowadays a plethora of SPICE versions are available. Rather than committing to a particular version, I have decided to keep schematic capture circuits simple enough for students to set them up in their preferred SPICE version in a matter of minutes.
- *Provide practical exposure to basic semiconductor concepts.* The majority of graduates from my own institution (a state university) pursue industrial careers spanning a wide range of positions from IC designers to product and reliability engineers, test and test-development engineers, and application and customer-support engineers, where a broad background is far more desirable than a narrow specialization. A basic understanding of semiconductor principles is an integral component of such a background, especially for future product and reliability engineers.
- *Make generous use of figures* to comply with today's visually oriented learning trends. Most figures consist of two or more components placed side by side to visualize different facets of the same concept, be they different states of a circuit, or models, or time frames, or cause-effect relationships (see Fig. 1.59, p. 69). Also, the most relevant formulas intervening in a given analytical process have

been boxed for easy visualization, especially when the student crams for quizzes and tests. When appropriate, entire groups of formulas have been tabulated to facilitate their comparison (see Fig. 3.50, p. 289).

I tried to address the above concerns by returning to an essential, no-frills, no-distractions textbook format. Each chapter starts with a brief historical background and motivational framework, followed by a brief outline of the topics to be covered, followed by the chapter body proper. It concludes with a variety of carefully thought-out problems emphasizing intuition and physical insight.

THE CONTENTS AT A GLANCE

Chapter 1 starts out with the *ideal diode* as a vehicle for introducing the student to nonlinear circuit analysis and applications. This is followed by a review of the *operational amplifier* to pave the way for additional applications of diodes and, later, transistors. It is now time to introduce the student to the most common physical device approximating the diode function, the *pn* junction. After an intuitive review of *semiconductors*, the *pn* junction is discussed in proper detail, using *rules of thumb* to highlight those practical aspects that engineers use daily on the job. Working familiarity with the *pn* junction is crucial for the understanding of transistor physics in the following two chapters. Finally, various *popular diode applications* are discussed, often using PSpice as a pedagogical aid to enhance understanding.

Chapter 2 introduces the *bipolar junction transistor* (BJT) as a technological (and historical) evolution of the *pn* junction. Mirroring Chapter 1, we start out with the *physical structure* of the BJT, followed by the derivation of its *i-v characteristics*, the development of *large- and small-signal models*, *dc biasing*, and finally the analysis and design of *single-transistor amplifiers* and *buffers*. The common-emitter configuration is presented as the natural realization of voltage amplification, whereas the common-collector and common-base configurations serve most naturally as voltage and current buffers, respectively. Great emphasis is placed on the role of the BJT as a *resistance transformation device* (which actually provided the basis for its very name.) The transformation equations are conveniently tabulated for easy reference in later chapters.

Chapter 3 covers the MOSFET in similar fashion as the BJT of Chapter 2. However, the two chapters are kept independent of each other, so the order of coverage can be interchanged if desired. The chapter begins with a detailed discussion of the physical basis of the *native threshold* for the benefit of those students who will pursue careers as product, process, and reliability engineers. Next the MOSFET's *i-v characteristics* are derived, followed by the development of *large- and small-signal models*, *dc biasing*, and finally the analysis and design of *single-transistor amplifiers* and *buffers*. The common-source configuration is presented as the natural realization of voltage amplification, whereas the common-drain and common-gate configurations serve most naturally as voltage and current buffers, respectively. The chapter also covers the *CMOS inverter* and basic CMOS *logic gates* so as to provide a more balanced treatment for the benefit of computer engineering majors (see the PSpice noise-margin illustration of Fig. 3.44, p. 281).

Chapter 4 brings the student to a higher level of circuit sophistication by introducing the analog IC *building blocks* in widest use today. *Cascode* configurations, *differential amplifiers*, *current mirrors* of all types, *active loads*, and *push-pull output stages* are treated in proper detail in anticipation of their utilization in the following chapter. Whenever possible, BJTs and MOSFETs are covered side by side so as to present the reader with a *uniform treatment* and thus save space as well as effort.

Chapter 5 puts to use the blocks of Chapter 4 in the design of a *representative mix* of analog ICs in both bipolar and CMOS technologies, namely: *high-gain amplifiers* such as op amps, voltage comparators, and fully-differential op amps; *voltage and current references* such as bandgap references; *current-mode ICs* such as transconductors, OTAs, and current-feedback amplifiers; and, finally, *switched-capacitor circuits*.

Chapter 6 deals with the *frequency and time responses* of individual devices all the way up to complex circuits such as the ICs of Chapter 5. Frequency analysis relies on the *Miller approximation* as well as the *open-circuit time-constant technique*. The switching times of *pn* diodes and BJTs, unjustifiably ignored by current textbooks in spite of their enduring industrial relevance, are investigated via *charge-control analysis* emphasizing physical insight. Also covered are the *switching times of CMOS gates* for the benefit of computer engineering majors. This is a chapter in which in-text PSpice is put to frequent use as a verification tool for hand calculations.

Chapter 7 starts out with a comprehensive treatment of *negative feedback* as applied to the electronic circuits of all previous chapters, from single-transistor stages all the way to op amps. Both *two-port* and *return-ratio analyses* are presented and compared via a variety of carefully thought out examples. Also *Blackman's impedance formula* and *injections methods* are presented in a practical manner. The chapter proceeds to the subject of *stability* and *frequency-compensation* for op amps, both bipolar and CMOS (here again PSpice proves a most useful pedagogical tool). The chapter concludes with the study of noise in integrated circuits. After an introduction to basic noise properties, analytical tools, and noise types, the noise models of diodes and transistors are discussed. Finally, noise analysis is applied to representative circuit configurations such as op amp circuits and differential pairs.

A WORD OF ADVICE TO THE STUDENT

Your electronics courses provide the foundation for your career in EE. The objective of these courses is not only to introduce you to new devices such as *diodes* and *transistors*, but also to help you establish a *thinking style* and develop a *problem-solving methodology* that are unique to this challenging but most interesting field. Cognizant of the fact that a large proportion of EE graduates end up working in industry, I have emphasized those practical aspects that are of relevance in today's industrial milieu. Whether you pursue a career as an IC designer, a product engineer, a test or test-development engineer, or an applications or customer support engineer, the basic material of your first electronics courses will always resurface in a variety of ever-changing situations, so you may wish to invest far more time and effort in this one course than you would normally do—the benefits will be quite rewarding.

Even though diodes and transistors are *highly nonlinear* devices, special techniques have been developed for their analysis, which draw quite heavily from those covered in linear-circuits courses. Far from being a waste of time, the analytical tools learned in these prerequisite courses will be put to heavy use also in the study of electronics. Specifically, *Ohm's law*, *Kirchhoff's laws* (KVL and KCL), *Nodal/Loop Analysis*, *Thévenin's/Norton's theorems*, the *Superposition principle*, and the *Op Amp Rule* will continue to be valuable analytical tools as we venture into the exciting realm of electronics.

Electronics, like any other branch of engineering, deals with the *physical reality* of its devices and systems. We use mathematics as a *tool* to understand or predict their operation as well as to design new ones, and computer simulation as a verification tool. Any conceptual derivation or prediction must ultimately be checked against physical substance and never be taken for granted on its own. The use of physical reasoning to corroborate any conceptual process, be it a mathematical derivation or a computer simulation, is at the very core of this entire course sequence.

Beside proficiency in linear circuit analysis techniques, the student is expected to possess a working knowledge of basic calculus concepts, such as slope and area under a curve, as well as basic electrostatics concepts such as Gauss's theorem and the relations between electric field and potential. Also, the ability to perform circuit simulations via PSpice, as learned in prerequisite circuits courses and labs, will prove extremely useful for checking the results of hand analysis.

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A number of reviewers provided detailed commentaries and many valuable suggestions. I tried to implement their recommendations whenever I could, but in the presence of conflicting viewpoints, I had to draw a line and pursue my own. To all who provided feedback, my sincere thanks. I would especially like to acknowledge Stephen Hubbard, Clemson University; Santosh Pandey, Iowa State University; and Donna Ginger Yu, North Carolina State University. Finally, I wish to express my gratitude to Diana May, my wife, for her encouragement and steadfast support.

Sergio Franco
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Diodes and the *pn* Junction

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The diode is the most basic electronic device. In fact, its invention, over a century ago, is credited with ushering in the era of *electronics*. Like the resistor, the diode comes with two terminals; however, unlike the bidirectional resistor, the diode carries current only in *one direction*. For a qualitative understanding of how this can happen, think of the early diodes, which were of the vacuum-tube type. A vacuum diode had an incandescent filament called a *cathode*, acting as a copious source of free electrons, and a plate called an *anode*, to control current flow. Applying a *positive* voltage to the anode relative to the cathode would attract the negatively charged electrons and thus *sustain electron flow* from cathode to anode. Conversely, applying a *negative* voltage to the anode would repel the electrons and thus *inhibit electron flow*. By a hydraulic analogy, the diode can be visualized as a *one-way valve*.

The vacuum-tube diode was invented by John A. Fleming in 1904. Just two years later, in 1906, Greenleaf W. Pickard invented an alternative diode type by forming a point contact to a slab of silicon, thus creating the first solid-state electronic device. However, it took half a century for the semiconductor industry to become a commercial reality, so the first half of the twentieth century was dominated by vacuum-tube electronics.

Nowadays diodes are made of *semiconductor materials*, with dramatic advantages over their vacuum-tube counterparts in terms of miniaturization, reliability, power consumption and cost. Specifically, the most common diode today is the silicon pn junction, though other types of materials and junctions are also in use. The pn junction plays a central role in microelectronics in that not only does it provide the diode function at the basis of the above applications, but it is also at the basis of the *bipolar junction transistor* (BJT), the *junction field-effect transistor* (JFET), and other semiconductor devices such as the *silicon-controlled rectifier* (SCR). The pn junction is also present in the *metal-oxide-semiconductor field-effect transistor* (MOSFET), the device most widely used in today's microelectronics products. Furthermore, in its reverse-biased form, the pn junction is used to *isolate* from each other different devices coexisting on the same semiconductor chip.

The student who comes from prerequisite courses in linear circuits will immediately find that diodes, like the transistors to follow, are highly *nonlinear* devices. Mercifully, a number of techniques have been developed for the analysis of nonlinear devices that draw quite heavily from those covered by linear-circuits courses. Far from being a waste of time, the analytical tools learned in circuits courses will also be put to heavy use in the study of electronics. Specifically, *Ohm's Law*, *Kirchhoff's Laws* (KVL and KCL), the *Voltage/Current Divider Rules*, *Thévenin's/Norton's Theorems*, and the *Superposition Principle* will continue to be our precious analytical tools as we venture into the exciting realm of electronic devices and systems.

CHAPTER HIGHLIGHTS

The chapter begins with the *ideal diode*, a concept designed to develop a basic feel for diode behavior as well as introduce the student to nonlinear circuit analysis techniques, the backbone of all subsequent electronics. The applications covered are *diode rectifiers*, *diode logic gates*, *voltage clamps*, *piecewise-linear function generators*, *peak detectors*, *dc restorers*, and *voltage multipliers*.

Next, we review the basic operational amplifier principles of prerequisite circuits courses because diodes (and later, transistors) offer a fertile application ground for op amps. The first diode-op-amp application to be considered is *full-wave rectification*, but others will follow as we proceed.

As mentioned, today diodes are made of semiconductors, so the next objective is the study of basic pn junction theory. After a review of the semiconductor basics normally covered in prerequisite physics courses, the chapter develops an intuitive discussion of the pn junction, highlighting those practical aspects (rules of thumb) that form the working knowledge of the electronics engineer in the modern industrial milieu. Whether the student will pursue a career as an IC designer, or a product, process, or reliability engineer, or as a test or applications engineer, the pn junction will