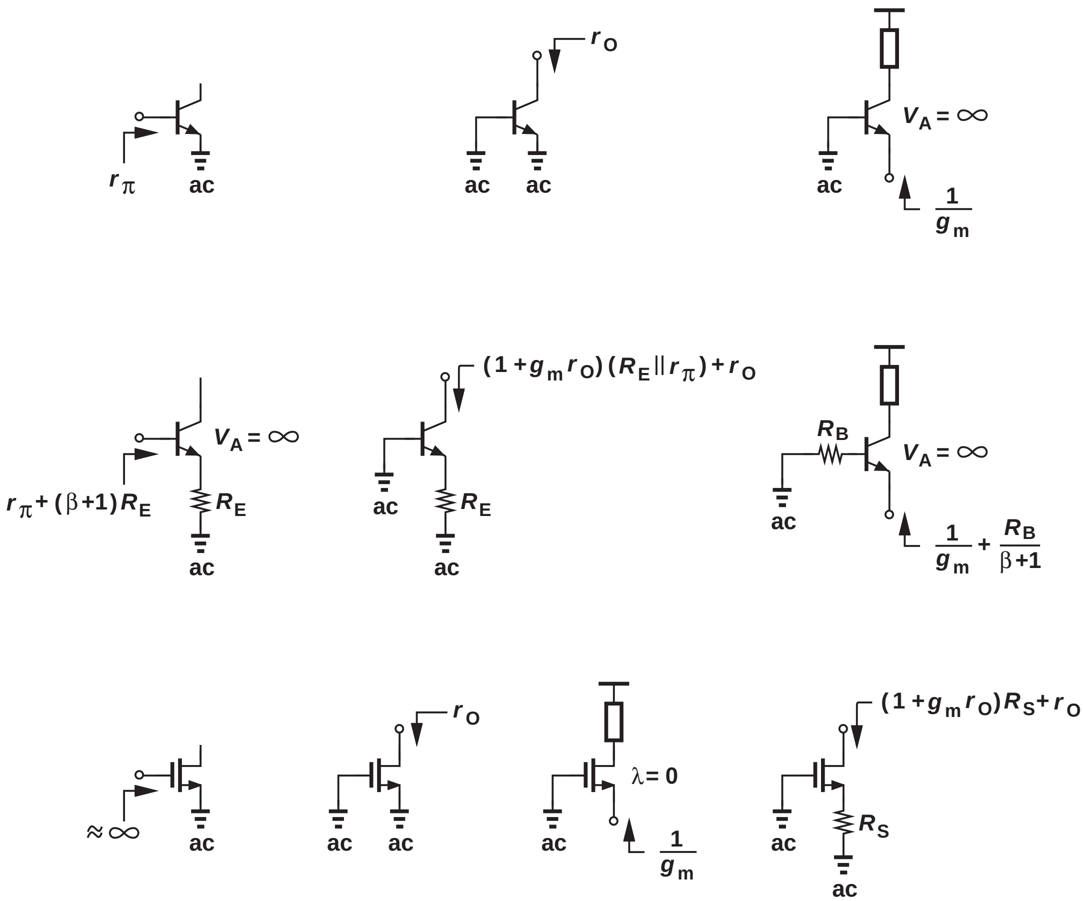
BEHZAD RAZAVI

Fundamentals of Microelectronics

SECOND EDITION

WILEY

Input and Output Impedances



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Second Edition

Behzad Razavi
University of California, Los Angeles

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To Angelina and Jahan,
for their love and patience

About the Author

Behzad Razavi received the BSEE degree from Sharif University of Technology in 1985 and the MSEE and PhDEE degrees from Stanford University in 1988 and 1992, respectively. He was with AT&T Bell Laboratories and Hewlett-Packard Laboratories until 1996. Since 1996, he has been Associate Professor and subsequently Professor of electrical engineering at University of California, Los Angeles. His current research includes wireless transceivers, frequency synthesizers, phase-locking and clock recovery for high-speed data communications, and data converters.

Professor Razavi was an Adjunct Professor at Princeton University from 1992 to 1994, and at Stanford University in 1995. He served on the Technical Program Committees of the International Solid-State Circuits Conference (ISSCC) from 1993 to 2002 and VLSI Circuits Symposium from 1998 to 2002. He has also served as Guest Editor and Associate Editor of the IEEE Journal of Solid-State Circuits, IEEE Transactions on Circuits and Systems, and International Journal of High Speed Electronics.

Professor Razavi received the Beatrice Winner Award for Editorial Excellence at the 1994 ISSCC, the best paper award at the 1994 European Solid-State Circuits Conference, the best panel award at the 1995 and 1997 ISSCC, the TRW Innovative Teaching Award in 1997, the best paper award at the IEEE Custom Integrated Circuits Conference in 1998, and the McGraw-Hill First Edition of the Year Award in 2001. He was the co-recipient of both the Jack Kilby Outstanding Student Paper Award and the Beatrice Winner Award for Editorial Excellence at the 2001 ISSCC. He received the Lockheed Martin Excellence in Teaching Award in 2006, the UCLA Faculty Senate Teaching Award in 2007, and the CICC Best Invited Paper Award in 2009 and 2012. He was the co-recipient of the 2012 VLSI Circuits Symposium Best Student Paper Award. He was also recognized as one of the top 10 authors in the 50-year history of ISSCC. Professor Razavi received the IEEE Donald Pederson Award in Solid-State Circuits in 2011.

Professor Razavi is a Fellow of IEEE, has served as an IEEE Distinguished Lecturer, and is the author of *Principles of Data Conversion System Design, RF Microelectronics* (translated to Chinese, Japanese, and Korean), *Design of Analog CMOS Integrated Circuits* (translated to Chinese, Japanese, and Korean), *Design of Integrated Circuits for Optical Communications*, and *Fundamentals of Microelectronics* (translated to Korean and Portuguese). He is also the editor of *Monolithic Phase-Locked Loops and Clock Recovery Circuits* and *Phase-Locking in High-Performance Systems*.

Preface

The first edition of this book was published in 2008 and has been adopted by numerous universities around the globe for undergraduate microelectronics education. In response to the feedback received from students and instructors, this second edition entails a number of revisions that enhance the pedagogical aspects of the book:

1. Numerous sidebars have been added throughout the text on the history and applications of electronic devices and circuits, helping the reader remain engaged and motivated and allowing the instructor to draw upon real-life examples during the lecture. The sidebars are intended to demonstrate the impact of electronics, elevate the reader's understanding of the concepts, or provide a snapshot of the latest developments in the field.
2. A chapter on oscillators has been added. A natural descendent of feedback circuits, discrete and integrated oscillators have become indispensible in most devices and hence merit a detailed study.
3. The end-of-chapter problems have been rearranged to better agree with the progression of the chapter. Also, to allow the reader to quickly find the problems for each section, the corresponding section titles have been added. Moreover, the challenging problems have been ranked in terms of their difficulty level by one or two stars.
4. Since students often ask for the answers to problems so as to check the validity of their approach, the answers to even-numbered problems have been posted on the book's website.
5. Various typographical errors have been corrected.

I wish to thank all of the students and instructors who have provided valuable feedback in the past five years and helped me decide on the revisions for this edition.

Behzad Razavi
January 2013

Preface to First Edition

With the advances in the semiconductor and communication industries, it has become increasingly important for electrical engineers to develop a good understanding of microelectronics. This book addresses the need for a text that teaches microelectronics from a modern and intuitive perspective. Guided by my industrial, research, and academic experience, I have chosen the topics, the order, and the depth and breadth so as to efficiently impart analysis and design principles that the students will find useful as they enter the industry or graduate school.

One salient feature of this book is its synthesis- or design-oriented approach. Rather than pulling a circuit out of a bag and trying to analyze it, I set the stage by stating a problem that we face in real life (e.g., how to design a cellphone charger). I then attempt to arrive at a solution using basic principles, thus presenting both failures and successes in the process. When we do arrive at the final solution, the student has seen the exact role of each device as well as the logical thought sequence behind synthesizing the circuit.

Another essential component of this book is "analysis by inspection." This "mentality" is created in two steps. First, the behavior of elementary building blocks is formulated using a "verbal" description of each analytical result (e.g., "looking into the emitter, we see $1/g_m$."). Second, larger circuits are decomposed and "mapped" to the elementary blocks to avoid the need for writing KVLs and KCLs. This approach both imparts a great deal of intuition and simplifies the analysis of large circuits.

The two articles following this preface provide helpful suggestions for students and instructors. I hope these suggestions make the task of learning or teaching microelectronics more enjoyable.

A set of Powerpoint slides, a solutions manual, and many other teaching aids are available for instructors.

Behzad Razavi
November 2007

Acknowledgments

This book has taken four years to write and benefited from contributions of many individuals. I wish to thank the following for their input at various stages of this book's development: David Allstot (University of Washington), Joel Berlinghieri, Sr. (The Citadel), Bernhard Boser (University of California, Berkeley), Charles Bray (University of Memphis), Marc Cahay (University of Cincinnati), Norman Cox (University of Missouri, Rolla), James Daley (University of Rhode Island), Tranjan Farid (University of North Carolina at Charlotte), Paul Furth (New Mexico State University), Roman Genov (University of Toronto), Maysam Ghovanloo (North Carolina State University), Gennady Gildenblat (Pennsylvania State University), Ashok Goel (Michigan Technological University), Michael Gouzman (SUNY, Stony Brook), Michael Green (University of California, Irvine), Sotoudeh Hamedi-Hagh (San Jose State University), Reid Harrison (University of Utah), Payam Heydari (University of California, Irvine), Feng Hua (Clarkson University), Marian Kazmierchuk (Wright State University), Roger King (University of Toledo), Edward Kolesar (Texas Christian University), Ying-Cheng Lai (Arizona State University), Daniel Lau (University of Kentucky, Lexington), Stanislaw Legowski (University of Wyoming), Philip Lopresti (University of Pennsylvania), Mani Mina (Iowa State University), James Morris (Portland State University), Khalil Najafi (University of Michigan), Homer Nazeran (University of Texas, El Paso), Tamara Papalias (San Jose State University), Matthew Radmanesh (California State University, Northridge), Angela Rasmussen (University of Utah), Sal R. Riggio, Jr. (Pennsylvania State University), Ali Sheikholeslami (University of Toronto), Kalpathy B. Sundaram (University of Central Florida), Yannis Tsividis (Columbia University), Thomas Wu (University of Central Florida), Darrin Young (Case Western Reserve University).

I am grateful to Naresh Shanbhag (University of Illinois, Urbana-Champaign) for test driving a draft of the book in a course and providing valuable feedback. The following UCLA students diligently prepared the solutions manual: Lawrence Au, Hamid Hatamkhani, Alireza Mehrnia, Alireza Razzaghi, William Wai-Kwok Tang, and Ning Wang. Ning Wang also produced the Powerpoint slides for the entire book. Eudean Sun (University of California, Berkeley) and John Tyler (Texas A&M University) served as accuracy checkers. I would like to thank them for their hard work.

I thank my publisher, Catherine Shultz, for her dedication and exuberance. Lucille Buonocore, Carmen Hernandez, Dana Kellogg, Madelyn Lesure, Christopher Ruel, Kenneth Santor, Lauren Sapira, Daniel Sayre, Gladys Soto, and Carolyn Weisman of Wiley and Bill Zobrist (formerly with Wiley) also deserve my gratitude. In addition, I wish to thank Jessica Knecht and Joyce Poh for their hard work on the second edition.

My wife, Angelina, typed the entire book and kept her humor as this project dragged on. My deepest thanks go to her.

Behzad Razavi

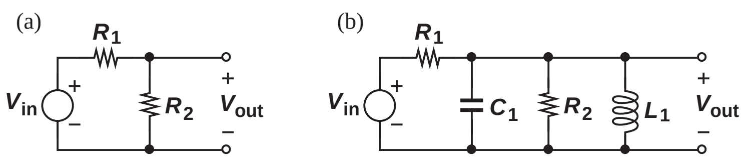
Suggestions for Students

You are about to embark upon a journey through the fascinating world of microelectronics. Fortunately, microelectronics appears in so many facets of our lives that we can readily gather enough motivation to study it. The reading, however, is not as easy as that of a novel; we must deal with *analysis* and *design*, applying mathematical rigor as well as engineering intuition every step of the way. This article provides some suggestions that students may find helpful in studying microelectronics.

Rigor and Intuition Before reading this book, you have taken one or two courses on basic circuit theory, mastering Kirchoff's Laws and the analysis of RLC circuits. While quite abstract and bearing no apparent connection with real life, the concepts studied in these courses form the foundation for microelectronics—just as calculus does for engineering.

Our treatment of microelectronics also requires rigor but entails two additional components. First, we identify many applications for the concepts that we study. Second, we must develop *intuition*, i.e., a "feel" for the operation of microelectronic devices and circuits. Without an intuitive understanding, the analysis of circuits becomes increasingly more difficult as we add more devices to perform more complex functions.

Analysis by Inspection We will expend a considerable effort toward establishing the mentality and the skills necessary for "analysis by inspection." That is, looking at a complex circuit, we wish to decompose or "map" it to simpler topologies, thus formulating the behavior with a few lines of algebra. As a simple example, suppose we have encountered the resistive divider shown in Fig. (a) and derived its Thevenin equivalent. Now, if given the circuit in Fig. (b), we can readily replace V_{in}, R_1, and R_2 with a Thevenin equivalent, thereby simplifying the calculations.



Example of analysis by inspections.

40 Pages per Week While taking courses on microelectronics, you will need to read about 40 pages of this book every week, with each page containing many new concepts, derivations, and examples. The lectures given by the instructor create a "skeleton" of each chapter, but it rests upon you to "connect the dots" by reading the book carefully and understanding each paragraph before proceeding to the next.

Reading and understanding 40 pages of the book each week requires concentration and discipline. You will face new material and detailed derivations on each page and should set aside two- or three-hour distraction-free blocks of time (no phone calls, TV, email, etc.) so that you can follow the *evolution* of the concepts while honing your analytical skills. I also suggest that you attempt each example before reading its solution.

40 Problems per Week After reading each section and going through its examples, you are encouraged to evaluate and improve your understanding by trying the corresponding end-of-chapter problems. The problems begin at a relatively easy level and gradually become more challenging. Some problems may require that you return to the section and study the subtle points more carefully.

The educational value provided by each problem depends on your *persistence*. The initial glance at the problem may be discouraging. But, as you think about it from different angles and, more importantly, re-examine the concepts in the chapter, you begin to form a path in your mind that may lead to the solution. In fact, if you have thought about a problem extensively and still have not solved it, you need but a brief hint from the instructor or the teaching assistant. Also, the more you struggle with a problem, the more appealing and memorable the answer will be.

Attending the lecture and reading the book are examples of "passive learning:" you simply receive (and, hopefully, absorb) a stream of information provided by the instructor and the text. While necessary, passive learning does not *exercise* your understanding, thus lacking depth. You may highlight many lines of the text as important. You may even summarize the important concepts on a separate sheet of paper (and you are encouraged to do so). But, to *master* the material, you need practice ("active learning"). The problem sets at the end of each chapter serve this purpose.

Homeworks and Exams Solving the problems at the end of each chapter also prepares you for homeworks and exams. Homeworks, too, demand distraction-free periods during which you put your knowledge to work and polish your understanding. An important piece of advice that I can offer here is that doing homeworks with your fellow students is a *bad* idea! Unlike other subject matters that benefit from discussions, arguments, and rebuttals, learning microelectronics requires quiet concentration. (After all, you will be on your own during the exam!) To gain more confidence in your answers, you can discuss the results with your fellow students, the instructor, or the teaching assistants *after* you have completed the homework by yourself.

Time Management Reading the text, going through the problem sets, and doing the homeworks require a time commitment of at least 10 hours per week. Due to the fast pace of the course, the material accumulates rapidly, making it difficult to keep up with the lectures if you do not spend the required time from the very first week. In fact, the more you fall behind, the less interesting and useful the lectures become, thus forcing you to simply write down everything that the instructor says while not understanding much. With your other courses demanding similar time commitments, you can soon become overwhelmed if you do not manage your time carefully.

Time management consists of two steps: (1) partitioning your waking hours into solid blocks, and (2) using each block *efficiently*. To improve the efficiency, you can take the following measures: (a) work in a quiet environment to minimize distractions; (b) spread the work on a given subject over the week, e.g., 3 hours every other day, to avoid saturation and to allow your subconscious to process the concepts in the meantime.

Prerequisites Many of the concepts that you have learned in the circuit theory courses prove essential to the study of microelectronics. Chapter 1 gives a brief overview to refresh your memory. With the limited lecture time, the instructor may not cover this material in the class, leaving it for you to read at home. You can first glance through the chapter and see which concepts "bother" you before sitting down to concentrate.

Suggestions for Instructors

Teaching undergraduate courses proves quite challenging—especially if the emphasis is on thinking and deduction rather than on memorization. With today's young minds used to playing fast-paced video games and "clicking" on the Internet toward their destination, it has become increasingly more difficult to encourage them to concentrate for long periods of time and deal with abstract concepts. Drawing upon more than one decade of teaching, this article provides suggestions that instructors of microelectronics may find helpful.

Therapy The students taking the first microelectronics course have typically completed one or two courses on basic circuit theory. To many, that experience has not been particularly memorable. After all, the circuit theory textbook is most likely written by a person *not* in the field of circuits. Similarly, the courses are most likely taught by an instructor having little involvement in circuit design. For example, the students are rarely told that node analysis is much more frequently used in hand calculations than mesh analysis is. Or, they are given little intuition with respect to Thevenin's and Norton's theorems.

With the foregoing issues in mind, I begin the first course with a five-minute "therapy session." I ask how many liked the circuit theory courses and came out with a "practical" understanding. Very few raise their hands. I then ask, "But how about your calculus courses? How many of you came out of these courses with a "practical" understanding?" Subsequently, I explain that circuit theory builds the foundation for microelectronics just as calculus does for engineering. I further mention that some abstractness should also be expected in microelectronics as we complete the foundation for more advanced topics in circuit analysis and design. I then point out that (1) microelectronics is very heavily based on intuitive understanding, requiring that we go *beyond* simply writing KVLs and KCLs and interpret the mathematical expressions intuitively, and (2) this course offers many applications of microelectronic devices and circuits in our daily lives. In other words, microelectronics is not as dry as arbitrary RLC circuits consisting of 1-Ω resistors, 1-H inductors, and 1-F capacitors.

First Quiz Since different students enter each course with different levels of preparation, I have found it useful to give a 10-minute quiz in the very first lecture. Pointing out that the quiz does not count towards their grade but serves as a gauge of their understanding, I emphasize that the objective is to test their knowledge rather than their intelligence. After collecting the quizzes, I ask one of the teaching assistants to assign a binary grade to each: those who would receive less than 50% are marked with a red star. At the end of the lecture, I return the quizzes and mention that those with a red star need to work harder and interact with the teaching assistants and myself more extensively.

The Big Picture A powerful motivational tool in teaching is the "big picture," i.e., the "practical" application of the concept under study. The two examples of microelectronic systems described in Chapter 1 serve as the first step toward creating the context for the material covered in the book. But, the big picture cannot stop here. Each new concept may merit an application—however brief the mention of the application may be—and most of this burden falls on the lecture rather than on the book.

The choice of the application must be carefully considered. If the description is too long or the result too abstract, the students miss the connection between the concept and the application. My general approach is as follows. Suppose we are to begin Chapter 2 (Basic Semiconductor Physics). I ask either "What would our world look like without semiconductors?" or "Is there a semiconductor device in your watch? In your cellphone? In your laptop? In your digital camera?" In the ensuing discussion, I quickly go over examples of semiconductor devices and where they are used.

Following the big picture, I provide additional motivation by asking, "Well, but isn't this stuff *old*? Why do *we* need to learn these things?" I then briefly talk about the challenges in today's designs and the competition among manufacturers to lower both the power consumption and the cost of portable devices.

Analysis versus Synthesis Let us consider the background of the students entering a microelectronics course. They can write KVLs and KCLs efficiently. They have also seen numerous "random" RLC circuits; i.e., to these students, all RLC circuits look the same, and it is unclear how they came about. On the other hand, an essential objective in teaching microelectronics is to develop specific circuit topologies that provide certain characteristics. We must therefore change the students' mentality from "Here's a circuit that you may never see again in your life. Analyze it!" to "We face the following problem and we must create (synthesize) a circuit that solves the problem." We can then begin with the simplest topology, identify its shortcomings, and continue to modify it until we arrive at an acceptable solution. This step-by-step synthesis approach (a) illustrates the role of each device in the circuit, (b) establishes a "design-oriented" mentality, and (c) engages the students' intellect and interest.

Analysis by Inspection In their journey through microelectronics, students face increasingly more complex circuits, eventually reaching a point where blindly writing KVLs and KCLs becomes extremely inefficient and even prohibitive. In one of my first few lectures, I show the internal circuit of a complex op amp and ask, "Can we analyze the behavior of this circuit by simply writing node or mesh equations?" It is therefore important to instill in them the concept of "analysis by inspection." My approach consists of two steps. (1) For each simple circuit, formulate the properties in an intuitive language; e.g., "the voltage gain of a common-source stage is given by the load resistance divided by $1/g_m$ plus the resistance tied from the source to ground." (2) Map complex circuits to one or more topologies studied in step (1).

In addition to efficiency, analysis by inspection also provides great intuition. As we cover various examples, I emphasize to the students that the results thus obtained reveal the circuit's dependencies much more clearly than if we simply write KVLs and KCLs without mapping.

"What If?" Adventures An interesting method of reinforcing a circuit's properties is to ask a question like, "What if we tie this device between nodes C and D rather than between nodes A and B?" In fact, students themselves often raise similar questions. My answer to them is "Don't be afraid! The circuit doesn't bite if you change it like this. So go ahead and analyze it in its new form."

For simple circuits, the students can be encouraged to consider several possible modifications and determine the resulting behavior. Consequently, the students feel much more comfortable with the original topology and understand why it is the only acceptable solution (if that is the case).

Numeric versus Symbolic Calculations In the design of examples, homeworks, and exams, the instructor must decide between numeric and symbolic calculations. The students may, of course, prefer the former type as it simply requires finding the corresponding equation and plugging in the numbers.

What is the value in numeric calculations? In my opinion, they may serve one of two purposes: (1) make the students comfortable with the results recently obtained, or (2) give the students a feel for the typical values encountered in practice. As such, numeric calculations play a limited role in teaching and reinforcing concepts.

Symbolic calculations, on the other hand, can offer insight into the behavior of the circuit by revealing dependencies, trends, and limits. Also, the results thus obtained can be utilized in more complex examples.

Blackboard versus Powerpoint This book comes with a complete set of Powerpoint slides. However, I suggest that the instructors carefully consider the pros and cons of blackboard and Powerpoint presentations.

I can offer the following observations. (1) Many students fall asleep (at least mentally) in the classroom if they are not writing. (2) Many others feel they are missing something if they are not writing. (3) For most people, the act of writing something on paper helps “carve” it in their mind. (4) The use of slides leads to a fast pace (“if we are not writing, we should move on!”), leaving little time for the students to digest the concepts. For these reasons, even if the students have a hardcopy of the slides, this type of presentation proves quite ineffective.

To improve the situation, one can leave blank spaces in each slide and fill them with critical and interesting results in real time. I have tried this method using transparencies and, more recently, tablet laptops. The approach works well for graduate courses but leaves undergraduate students bored or bewildered.

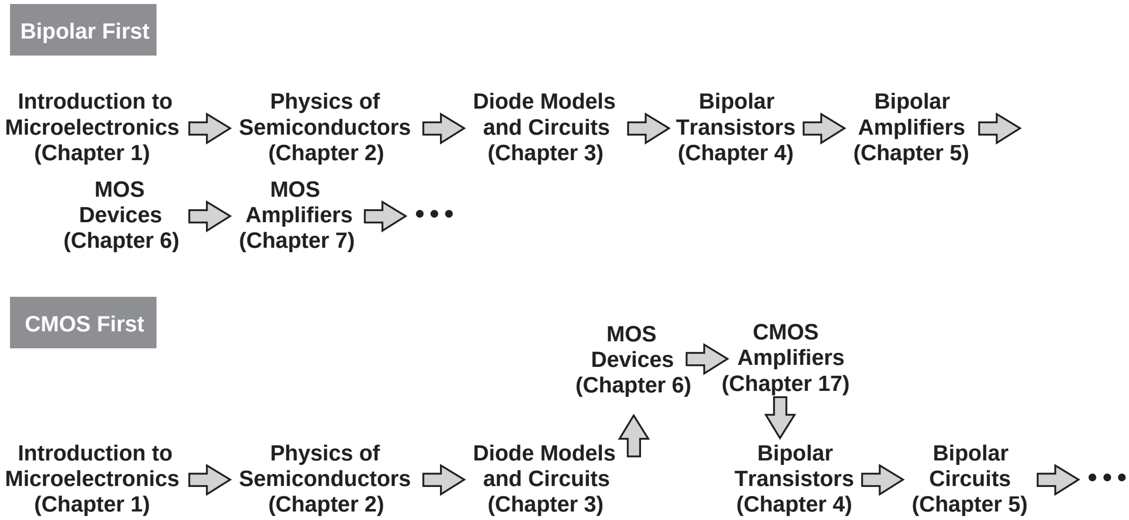
My conclusion is that the good old blackboard is still the best medium for teaching undergraduate microelectronics. The instructor may nonetheless utilize a hardcopy of the Powerpoint slides as his/her own guide for the flow of the lecture.

Discrete versus Integrated How much emphasis should a microelectronics course place on discrete circuits and integrated circuits? To most of us, the term “microelectronics” remains synonymous with “integrated circuits,” and, in fact, some university curricula have gradually reduced the discrete design flavor of the course to nearly zero. However, only a small fraction of the students taking such courses eventually become active in IC products, while many go into board-level design.

My approach in this book is to begin with general concepts that apply to both paradigms and gradually concentrate on integrated circuits. I also believe that even board-level designers must have a basic understanding of the integrated circuits that they use.

Bipolar Transistor versus MOSFET At present, some controversy surrounds the inclusion of bipolar transistors and circuits in undergraduate microelectronics. With the MOSFET dominating the semiconductor market, it appears that bipolar devices are of little value. While this view may apply to graduate courses to some extent, it should be borne in mind that (1) as mentioned above, many undergraduate students go into board-level and discrete design and are likely to encounter bipolar devices, and (2) the contrasts and similarities between bipolar and MOS devices prove extremely useful in understanding the properties of each.

The order in which the two species are presented is also debatable. (Extensive surveys conducted by Wiley indicate a 50-50 split between instructors on this matter.) Some



Course sequences for covering bipolar technology first or CMOS technology first.

instructors begin with MOS devices to ensure enough time is spent on their coverage. On the other hand, the natural flow of the course calls for bipolar devices as an extension of *pn* junctions. In fact, if diodes are immediately followed by MOS devices, the students see little relevance between the two. (The *pn* junctions in MOSFETs do not come into the picture until the device capacitances are introduced.)

My approach in this book is to first cover bipolar devices and circuits while building the foundation such that the MOS counterparts are subsequently taught with greater ease. As explained below, the material can comfortably be taught even in one quarter with no sacrifice of details of either device type.

Nonetheless, the book is organized so as to allow covering CMOS circuits first if the instructor so wishes. The sequence of chapters for each case is shown below. Chapter 16 is written with the assumption that the students have not seen any amplifier design principles so that the instructor can seamlessly go from MOS device phyics to MOS amplifier design without having covered bipolar amplifiers.

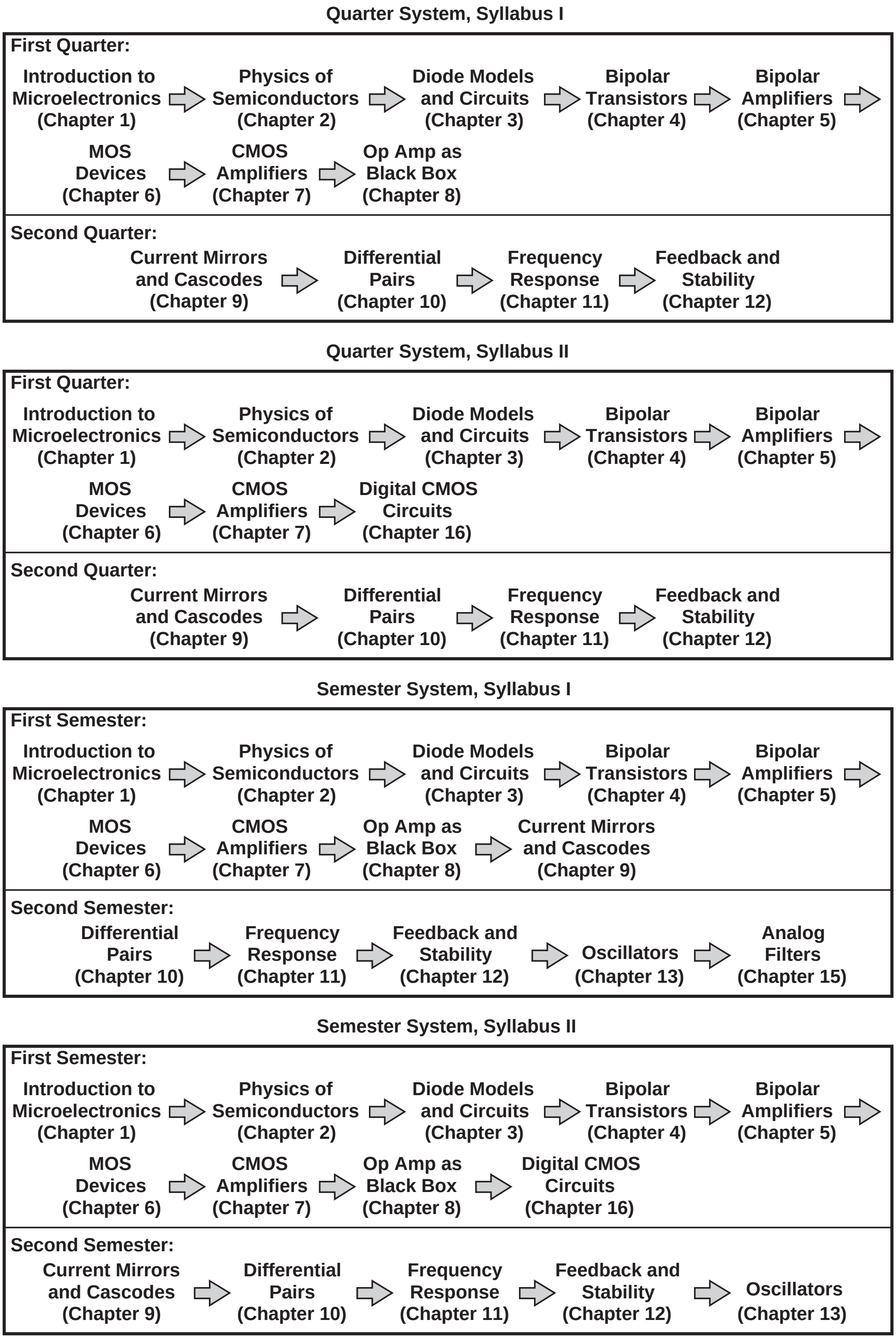
Course Syllabi This book can be used in a two-quarter or two-semester sequence. Depending on the instructor's preference, the courses can follow various combinations of the chapters. Figure illustrates some possibilities.

I have followed Syllabus I for the quarter system at UCLA for a number of years.[1] Syllabus II sacrifices op amp circuits for an introductory treatment of digital CMOS circuits.

In a semester system, Syllabus I extends the first course to current mirrors and cascode stages and the second course to output stages and analog filters. Syllabus II, on the other hand, includes digital circuits in the first course, moving current mirrors and cascodes to the second course and sacrificing the chapter on output stages.

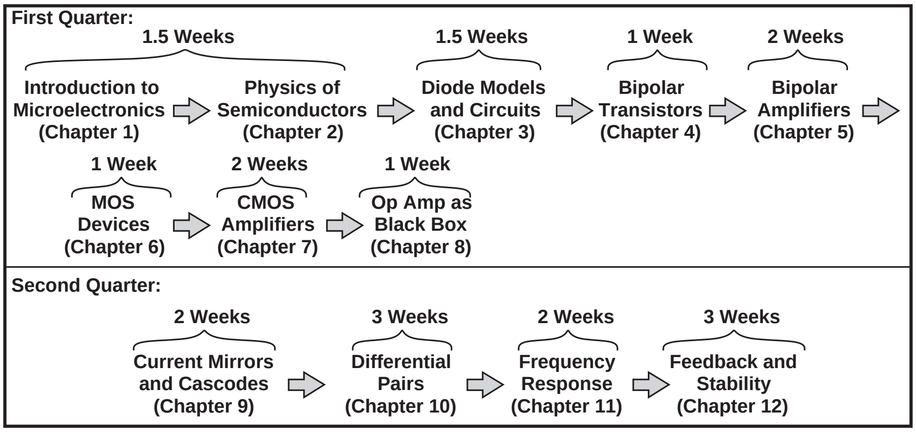
Figure shows the approximate length of time spent on the chapters as practiced at UCLA. In a semester system, the allotted times are more flexible.

[1]We offer a separate undergraduate course on digital circuit design, which the students can take only *after* our first microelectronics course.



Different course structures for quarter and semester systems.

Quarter System, Syllabus I



Timetable for the two courses.

Coverage of Chapters The material in each chapter can be decomposed into three categories: (1) essential concepts that the instructor should cover in the lecture, (2) essential skills that the students must develop but cannot be covered in the lecture due to the limited time, and (3) topics that prove useful but may be skipped according to the instructor's preference.[2] Summarized below are overviews of the chapters showing which topics should be covered in the classroom.

Chapter 1: Introduction to Microelectronics The objective of this chapter is to provide the "big picture" and make the students comfortable with analog and digital signals. I spend about 30 to 45 minutes on Sections 1.1 and 1.2, leaving the remainder of the chapter (Basic Concepts) for the teaching assistants to cover in a special evening session in the first week.

Chapter 2: Basic Semiconductor Physics Providing the basics of semiconductor device physics, this chapter deliberately proceeds at a slow pace, examining concepts from different angles and allowing the students to digest the material as they read on. A terse language would shorten the chapter but require that the students reread the material multiple times in their attempt to decipher the prose.

It is important to note, however, that the instructor's pace in the classroom need not be as slow as that of the chapter. The students are expected to read the details and the examples on their own so as to strengthen their grasp of the material. The principal point in this chapter is that we must study the physics of devices so as to construct circuit models for them. In a quarter system, I cover the following concepts in the lecture: electrons and holes; doping; drift and diffusion; *pn* junction in equilibrium and under forward and reverse bias.

Chapter 3: Diode Models and Circuits This chapter serves four purposes: (1) make the students comfortable with the *pn* junction as a nonlinear device; (2) introduce the concept of linearizing a nonlinear model to simplify the analysis; (3) cover basic circuits with which any electrical engineer must be familiar, e.g., rectifiers and limiters; and (4) develop the

[2]Such topics are identified in the book by a footnote.

skills necessary to analyze heavily-nonlinear circuits, e.g., where it is difficult to predict which diode turns on at what input voltage. Of these, the first three are essential and should be covered in the lecture, whereas the last depends on the instructor's preference. (I cover it in my lectures.) In the interest of time, I skip a number of sections in a quarter system, e.g., voltage doublers and level shifters.

Chapter 4: Physics of Bipolar Transistors Beginning with the use of a voltage-controlled current source in an amplifier, this chapter introduces the bipolar transistor as an extension of *pn* junctions and derives its small-signal model. As with Chapter 2, the pace is relatively slow, but the lectures need not be. I cover structure and operation of the bipolar transistor, a very simplified derivation of the exponential characteristic, and transistor models, mentioning only briefly that saturation is undesirable. Since the T-model of limited use in analysis and carries little intuition (especially for MOS devices), I have excluded it in this book.

Chapter 5: Bipolar Amplifiers This is the longest chapter in the book, building the foundation necessary for all subsequent work in electronics. Following a bottom-up approach, this chapter establishes critical concepts such as input and output impedances, biasing, and small-signal analysis.

While writing the book, I contemplated decomposing Chapter 5 into two chapters, one on the above concepts and another on bipolar amplifier topologies, so that the latter could be skipped by instructors who prefer to continue with MOS circuits instead. However, teaching the general concepts does require the use of transistors, making such a decomposition difficult.

Chapter 5 proceeds slowly, reinforcing, step-by-step, the concept of synthesis and exploring circuit topologies with the aid of "What if?" examples. As with Chapters 2 and 4, the instructor can move at a faster pace and leave much of the text for the students to read on their own. In a quarter system, I cover all of the chapter, frequently emphasizing the concepts illustrated in Figure 5.7 (the impedance seen looking into the base, emitter, or collector). With about two (perhaps two and half) weeks allotted to this chapter, the lectures must be precisely designed to ensure the main concepts are imparted in the classroom.

Chapter 6: Physics of MOS Devices This chapter parallels Chapter 4, introducing the MOSFET as a voltage-controlled current source and deriving its characteristics. Given the limited time that we generally face in covering topics, I have included only a brief discussion of the body effect and velocity saturation and neglected these phenomena for the remainder of the book. I cover all of this chapter in our first course.

Chapter 7: CMOS Amplifiers Drawing extensively upon the foundation established in Chapter 5, this chapter deals with MOS amplifiers but at a faster pace. I cover all of this chapter in our first course.

Chapter 8: Operational Amplifier as a Black Box Dealing with op-amp-based circuits, this chapter is written such that it can be taught in almost any order with respect to other chapters. My own preference is to cover this chapter *after* amplifier topologies have been studied, so that the students have some bare understanding of the internal circuitry of op amps and its gain limitations. Teaching this chapter near the end of the first course also places op amps closer to differential amplifiers (Chapter 10), thus allowing the students to appreciate the relevance of each. I cover all of this chapter in our first course.

Chapter 9: Cascodes and Current Mirrors This chapter serves as an important step toward integrated circuit design. The study of cascodes and current mirrors here also provides the necessary background for constructing differential pairs with active loads or cascodes in Chapter 10. From this chapter on, bipolar and MOS circuits are covered together and various similarities and contrasts between them are pointed out. In our second microelectronics course, I cover all of the topics in this chapter in approximately two weeks.

Chapter 10: Differential Amplifiers This chapter deals with large-signal and small-signal behavior of differential amplifiers. The students may wonder why we did not study the large-signal behavior of various amplifiers in Chapters 5 and 7; so I explain that the differential pair is a versatile circuit and is utilized in both regimes. I cover all of this chapter in our second course.

Chapter 11: Frequency Response Beginning with a review of basic concepts such as Bode's rules, this chapter introduces the high-frequency model of transistors and analyzes the frequency response of basic amplifiers. I cover all of this chapter in our second course.

Chapter 12: Feedback and Stability Most instructors agree the students find feedback to be the most difficult topic in undergraduate microelectronics. For this reason, I have made great effort to create a step-by-step procedure for analyzing feedback circuits, especially where input and output loading effects must be taken into account. As with Chapters 2 and 5, this chapter proceeds at a deliberately slow pace, allowing the students to become comfortable with each concept and appreciate the points taught by each example. I cover all of this chapter in our second course.

Chapter 13: Oscillators This new chapter deals with both discrete and integrated oscillators. These circuits are both important in real-life applications and helpful in enhancing the feedback concepts taught previously. This chapter can be comfortably covered in a semester system.

Chapter 14: Output Stages and Power Amplifiers This chapter studies circuits that deliver higher power levels than those considered in previous chapters. Topologies such as push-pull stages and their limitations are analyzed. This chapter can be covered in a semester system.

Chapter 15: Analog Filters This chapter provides a basic understanding of passive and active filters, preparing the student for more advanced texts on the subject. This chapter can also be comfortably covered in a semester system.

Chapter 16: Digital CMOS Circuits This chapter is written for microelectronics courses that include an introduction to digital circuits as a preparation for subsequent courses on the subject. Given the time constraints in quarter and semester systems, I have excluded TTL and ECL circuits here.

Chapter 17: CMOS Amplifiers This chapter is written for courses that cover CMOS circuits before bipolar circuits. As explained earlier, this chapter follows MOS device physics and, in essence, is similar to Chapter 5 but deals with MOS counterparts.

Problem Sets In addition to numerous examples, each chapter offers a relatively large problem set at the end. For each concept covered in the chapter, I begin with simple, confidence-building problems and gradually raise the level of difficulty. Except for the device physics chapters, all chapters also provide a set of design problems that encourage students to work "in reverse" and select the bias and/or component values to satisfy certain requirements.

SPICE Some basic circuit theory courses may provide exposure to SPICE, but it is in the first microelectronics course that the students can appreciate the importance of simulation tools. Appendix A of this book introduces SPICE and teaches circuit simulation with the aid of numerous examples. The objective is to master only a *subset* of SPICE commands that allow simulation of most circuits at this level. Due to the limited lecture time, I ask the teaching assistants to cover SPICE in a special evening session around the middle of the quarter—just before I begin to assign SPICE problems.

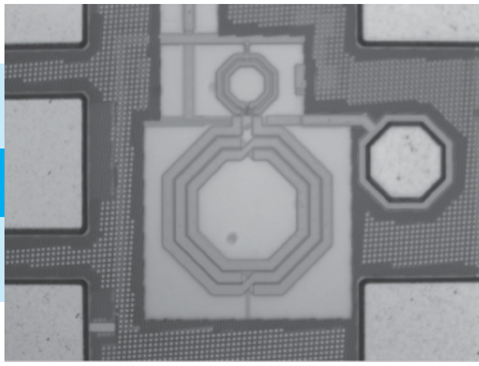
Most chapters contain SPICE problems, but I prefer to introduce SPICE only in the second half of the first course (toward the end of Chapter 5). This is for two reasons: (1) the students must first develop their basic understanding and analytical skills, i.e., the homeworks must exercise the fundamental concepts; and (2) the students appreciate the utility of SPICE much better if the circuit contains a relatively large number of devices (e.g., 5-10).

Homeworks and Exams In a quarter system, I assign four homeworks before the midterm and four after. Mostly based on the problem sets in the book, the homeworks contain moderate to difficult problems, thereby requiring that the students first go over the easier problems in the book on their own.

The exam questions are typically "twisted" versions of the problems in the book. To encourage the students to solve *all* of the problems at the end of each chapter, I tell them that one of the problems in the book is given in the exam verbatim. The exams are open-book, but I suggest to the students to summarize the important equations on one sheet of paper.

Happy Teaching!

Contents



1

Introduction to Microelectronics

Over the past five decades, microelectronics has revolutionized our lives. While beyond the realm of possibility a few decades ago, cellphones, digital cameras, laptop computers, and many other electronic products have now become an integral part of our daily affairs.

Learning microelectronics *can* be fun. As we learn how each device operates, how devices comprise circuits that perform interesting and useful functions, and how circuits form sophisticated systems, we begin to see the beauty of microelectronics and appreciate the reasons for its explosive growth.

This chapter gives an overview of microelectronics so as to provide a context for the material presented in this book. We introduce examples of microelectronic systems and identify important circuit "functions" that they employ. We also provide a review of basic circuit theory to refresh the reader's memory.

1.1 ELECTRONICS VERSUS MICROELECTRONICS

The general area of electronics began about a century ago and proved instrumental in the radio and radar communications used during the two world wars. Early systems incorporated "vacuum tubes," amplifying devices that operated with the flow of electrons between plates in a vacuum chamber. However, the finite lifetime and the large size of vacuum tubes motivated researchers to seek an electronic device with better properties.

The first transistor was invented in the 1940s and rapidly displaced vacuum tubes. It exhibited a very long (in principle, infinite) lifetime and occupied a much smaller volume (e.g., less than 1 cm^3 in packaged form) than vacuum tubes did.

But it was not until 1960s that the field of microelectronics, i.e., the science of integrating many transistors on one chip, began. Early "integrated circuits" (ICs) contained only a handful of devices, but advances in the technology soon made it possible to dramatically increase the complexity of "microchips."

Example 1.1

Today's microprocessors contain about 100 million transistors in a chip area of approximately 3 cm × 3 cm. (The chip is a few hundred microns thick.) Suppose integrated circuits were not invented and we attempted to build a processor using 100 million "discrete" transistors. If each device occupies a volume of 3 mm × 3 mm × 3 mm, determine the minimum volume for the processor. What other issues would arise in such an implementation?

Solution

The minimum volume is given by $27\ \text{mm}^3 \times 10^8$, i.e., a cube 1.4 m on each side! Of course, the wires connecting the transistors would increase the volume substantially.

In addition to occupying a large volume, this discrete processor would be extremely *slow*; the signals would need to travel on wires as long as 1.4 m! Furthermore, if each discrete transistor costs 1 cent and weighs 1 g, each processor unit would be priced at one million dollars and weigh 100 tons!

Exercise How much power would such a system consume if each transistor dissipates 10 μW?

This book deals mostly with microelectronics while providing sufficient foundation for general (perhaps discrete) electronic systems as well.

1.2 EXAMPLES OF ELECTRONIC SYSTEMS

At this point, we introduce two examples of microelectronic systems and identify some of the important building blocks that we should study in basic electronics.

1.2.1 Cellular Telephone

Cellular telephones were developed in the 1980s and rapidly became popular in the 1990s. Today's cellphones contain a great deal of sophisticated analog and digital electronics that lie well beyond the scope of this book. But our objective here is to see how the concepts described in this book prove relevant to the operation of a cellphone.

Suppose you are speaking with a friend on your cellphone. Your voice is converted to an electric signal by a microphone and, after some processing, transmitted by the antenna. The signal produced by your antenna is picked up by your friend's receiver and, after some processing, applied to the speaker [Fig. 1.1(a)]. What goes on in these black boxes? Why are they needed?

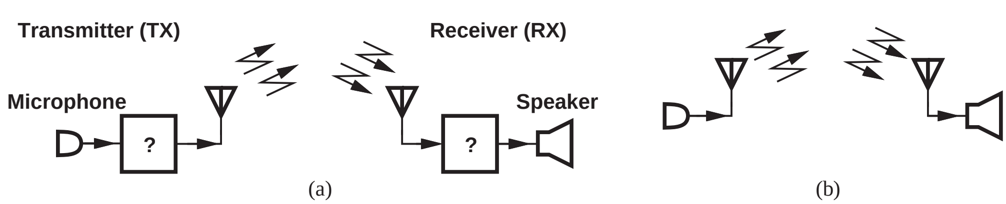


Figure 1.1 (a) Simplified view of a cellphone, (b) further simplification of transmit and receive paths.

Let us attempt to omit the black boxes and construct the simple system shown in Fig. 1.1(b). How well does this system work? We make two observations. First, our voice contains frequencies from 20 Hz to 20 kHz (called the "voice band"). Second, for an antenna to operate efficiently, i.e., to convert most of the electrical signal to electromagnetic radiation, its dimension must be a significant fraction (e.g., 25%) of the wavelength. Unfortunately, a frequency range of 20 Hz to 20 kHz translates to a wavelength[1] of 1.5×10^7 m to 1.5×10^4 m, requiring gigantic antennas for each cellphone. Conversely, to obtain a reasonable antenna length, e.g., 5 cm, the wavelength must be around 20 cm and the frequency around 1.5 GHz.

How do we "convert" the voice band to a gigahertz center frequency? One possible approach is to multiply the voice signal, $x(t)$, by a sinusoid, $A\cos(2\pi f_c t)$ [Fig. 1.2(a)]. Since multiplication in the time domain corresponds to convolution in the frequency domain, and since the spectrum of the sinusoid consists of two impulses at $\pm f_c$, the voice spectrum is simply shifted (translated) to $\pm f_c$ [Fig. 1.2(b)]. Thus, if $f_c = 1$ GHz, the output occupies a bandwidth of 40 kHz centered at 1 GHz. This operation is an example of "amplitude modulation."[2]

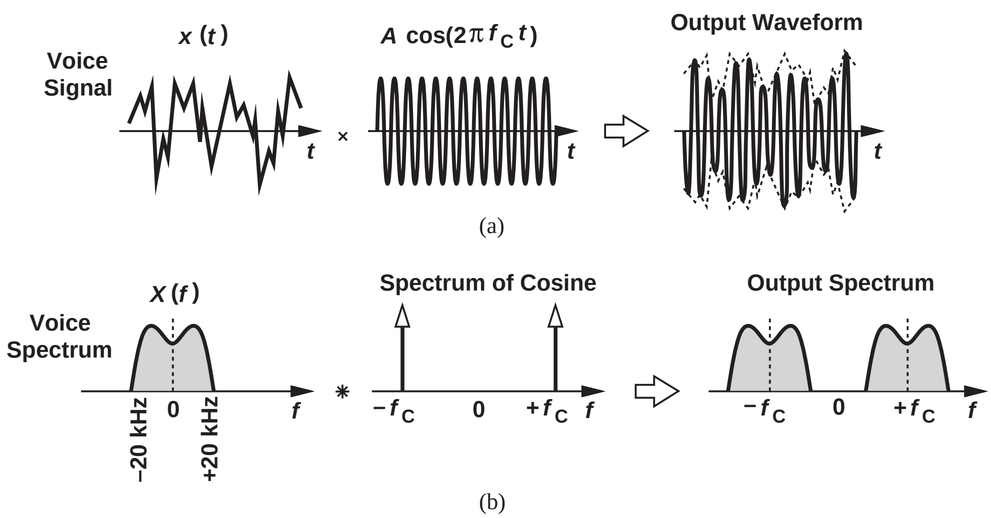


Figure 1.2 (a) Multiplication of a voice signal by a sinusoid, (b) equivalent operation in the frequency domain.

We therefore postulate that the black box in the transmitter of Fig. 1.1(a) contains a multiplier,[3] as depicted in Fig. 1.3(a). But two other issues arise. First, the cellphone must deliver a relatively large voltage swing (e.g., 20 V_{pp}) to the antenna so that the radiated power can reach across distances of several kilometers, thereby requiring a "power amplifier" between the multiplier and the antenna. Second, the sinusoid, $A\cos 2\pi f_c t$, must be produced by an "oscillator." We thus arrive at the transmitter architecture shown in Fig. 1.3(b).

[1] Recall that the wavelength is equal to the (light) velocity divided by the frequency.

[2] Cellphones in fact use other types of modulation to translate the voice band to higher frequencies.

[3] Also called a "mixer" in high-frequency electronics.

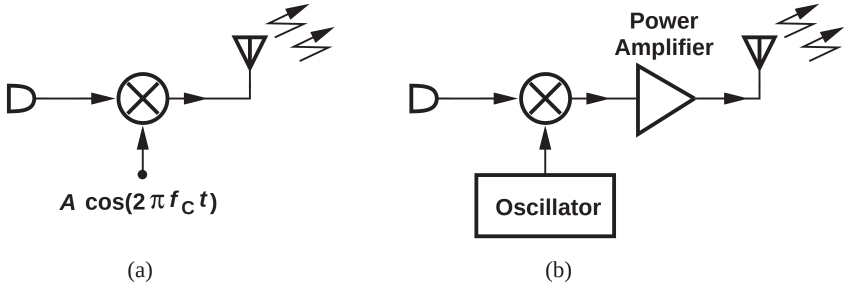


Figure 1.3 (a) Simple transmitter, (b) more complete transmitter.

Let us now turn our attention to the receive path of the cellphone, beginning with the simple realization illustrated in Fig. 1.1(b). Unfortunately, this topology fails to operate with the principle of modulation: if the signal received by the antenna resides around a gigahertz center frequency, the audio speaker cannot produce meaningful information. In other words, a means of translating the spectrum back to zero center frequency is necessary. For example, as depicted in Fig. 1.4(a), multiplication by a sinusoid, $A\cos(2\pi f_c t)$, translates the spectrum to left and right by f_c, restoring the original voice band. The newly-generated components at $\pm 2f_c$ can be removed by a low-pass filter. We thus arrive at the receiver topology shown in Fig. 1.4(b).

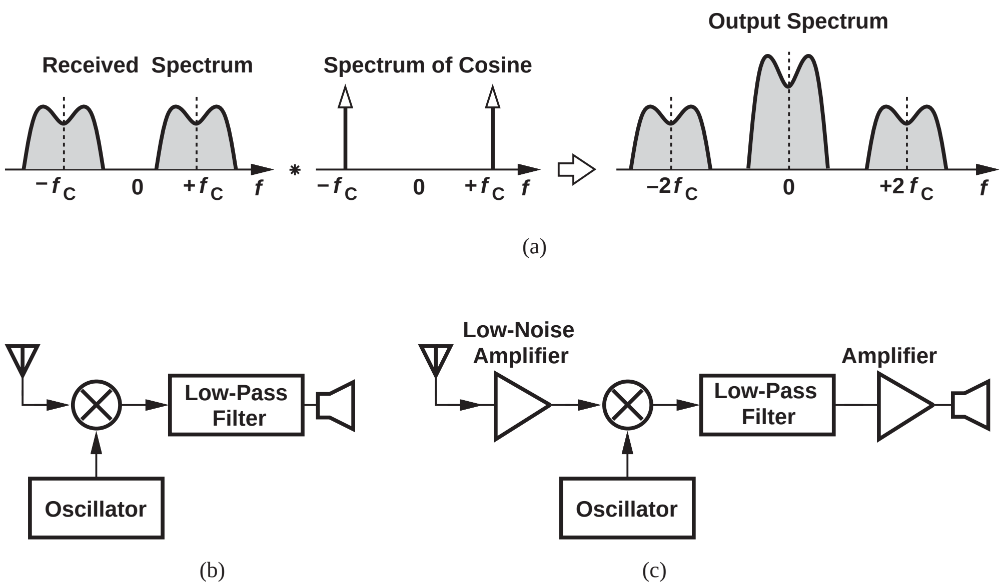


Figure 1.4 (a) Translation of modulated signal to zero center frequency, (b) simple receiver, (b) more complete receiver.

Our receiver design is still incomplete. The signal received by the antenna can be as low as a few tens of microvolts whereas the speaker may require swings of several tens or hundreds of millivolts. That is, the receiver must provide a great deal of amplification ("gain") between the antenna and the speaker. Furthermore, since multipliers typically suffer from a high "noise" and hence corrupt the received signal, a "low-noise amplifier" must precede the multiplier. The overall architecture is depicted in Fig. 1.4(c).

Today's cellphones are much more sophisticated than the topologies developed above. For example, the voice signal in the transmitter and the receiver is applied to a digital signal processor (DSP) to improve the quality and efficiency of the communication. Nonetheless, our study reveals some of the *fundamental* building blocks of cellphones, e.g., amplifiers, oscillators, and filters, with the last two also utilizing amplification. We therefore devote a great deal of effort to the analysis and design of amplifiers.

Having seen the necessity of amplifiers, oscillators, and multipliers in both transmit and receive paths of a cellphone, the reader may wonder if "this is old stuff" and rather trivial compared to the state of the art. Interestingly, these building blocks still remain among the most challenging circuits in communication systems. This is because the design entails critical *trade-offs* between speed (gigahertz center frequencies), noise, power dissipation (i.e., battery lifetime), weight, cost (i.e., price of a cellphone), and many other parameters. In the competitive world of cellphone manufacturing, a given design is never "good enough" and the engineers are forced to further push the above trade-offs in each new generation of the product.

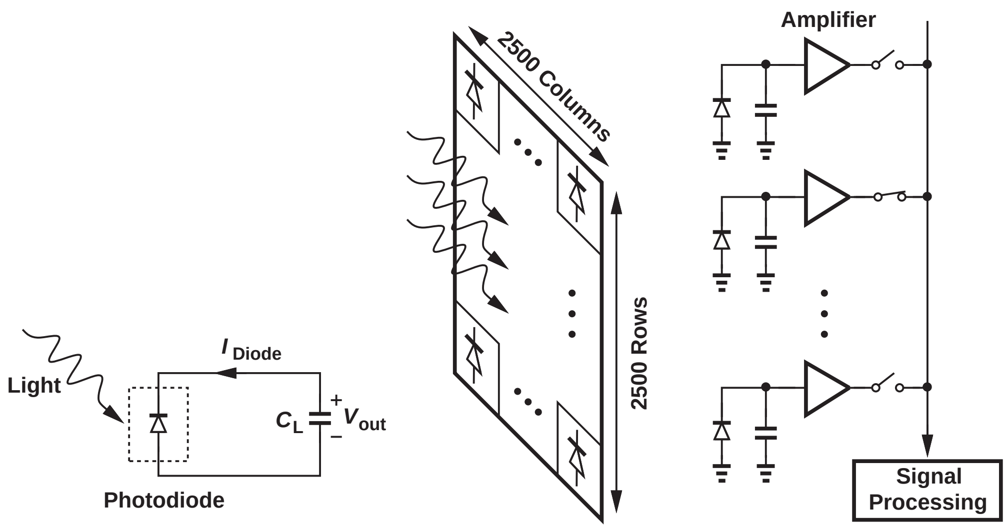
1.2.2 Digital Camera

Another consumer product that, by virtue of "going electronic," has dramatically changed our habits and routines is the digital camera. With traditional cameras, we received no immediate feedback on the quality of the picture that was taken, we were very careful in selecting and shooting scenes to avoid wasting frames, we needed to carry bulky rolls of film, and we would obtain the final result only in printed form. With digital cameras, on the other hand, we have resolved these issues and enjoy many other features that only electronic processing can provide, e.g., transmission of pictures through cellphones or ability to retouch or alter pictures by computers. In this section, we study the operation of the digital camera.

The "front end" of the camera must convert light to electricity, a task performed by an array (matrix) of "pixels."[4] Each pixel consists of an electronic device (a "photodiode") that produces a current proportional to the intensity of the light that it receives. As illustrated in Fig. 1.5(a), this current flows through a capacitance, C_L, for a certain period of time, thereby developing a proportional voltage across it. Each pixel thus provides a voltage proportional to the "local" light density.

Now consider a camera with, say, 6.25 million pixels arranged in a 2500×2500 array [Fig. 1.5(b)]. How is the output voltage of each pixel sensed and processed? If each pixel contains its own electronic circuitry, the overall array occupies a very large area, raising the cost and the power dissipation considerably. We must therefore "time-share" the signal processing circuits among pixels. To this end, we follow the circuit of Fig. 1.5(a) with a simple, compact amplifier and a switch (within the pixel) [Fig. 1.5(c)]. Now, we connect a wire to the outputs of all 2500 pixels in a "column," turn on only one switch at a time, and apply the corresponding voltage to the "signal processing" block outside the column.

[4]The term "pixel" is an abbreviation of "picture cell."



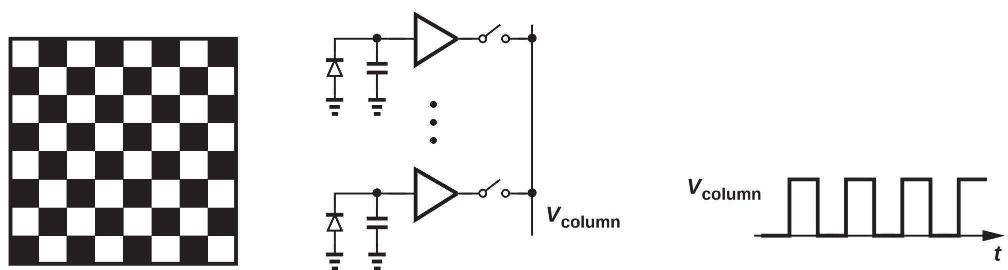
(a) (b) (c)

Figure 1.5 (a) Operation of a photodiode, (b) array of pixels in a digital camera, (c) one column of the array.

The overall array consists of 2500 of such columns, with each column employing a dedicated signal processing block.

Example 1.2 A digital camera is focused on a chess board. Sketch the voltage produced by one column as a function of time.

Solution The pixels in each column receive light only from the white squares [Fig. 1.6(a)]. Thus, the column voltage alternates between a maximum for such pixels and zero for those receiving no light. The resulting waveform is shown in Fig. 1.6(b).



(a) (b) (c)

Figure 1.6 (a) Chess board captured by a digital camera, (b) voltage waveform of one column.

Exercise Plot the voltage if the first and second squares in each row have the same color.

What does each signal processing block do? Since the voltage produced by each pixel is an analog signal and can assume all values within a range, we must first "digitize" it by means of an "analog-to-digital converter" (ADC). A 6.25 megapixel array must thus incorporate 2500 ADCs. Since ADCs are relatively complex circuits, we may time-share one ADC between every two columns (Fig. 1.7), but requiring that the ADC operate twice as fast (why?). In the extreme case, we may employ a single, very fast ADC for all 2500 columns. In practice, the optimum choice lies between these two extremes.

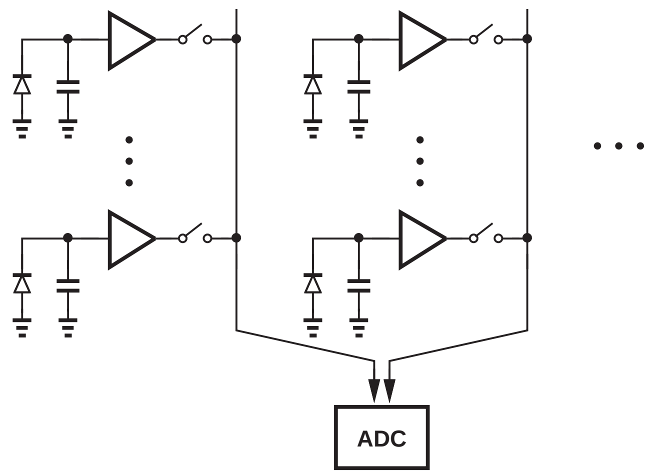


Figure 1.7 Sharing one ADC between two columns of a pixel array.

Once in the digital domain, the "video" signal collected by the camera can be manipulated extensively. For example, to "zoom in," the digital signal processor (DSP) simply considers only a section of the array, discarding the information from the remaining pixels. Also, to reduce the required memory size, the processor "compresses" the video signal.

The digital camera exemplifies the extensive use of both analog and digital microelectronics. The analog functions include amplification, switching operations, and analog-to-digital conversion, and the digital functions consist of subsequent signal processing and storage.

1.2.3 Analog Versus Digital

Amplifiers and ADCs are examples of analog functions, circuits that must process each point on a waveform (e.g., a voice signal) with great care to avoid effects such as noise and "distortion." By contrast, digital circuits deal with binary levels (ONEs and ZEROs) and, evidently, contain no analog functions. The reader may then say, "I have no intention of working for a cellphone or camera manufacturer and, therefore, need not learn about analog circuits." In fact, with digital communications, digital signal processors, and every other function becoming digital, is there any future for analog design?

Well, some of the assumptions in the above statements are incorrect. First, not every function can be realized digitally. The architectures of Figs. 1.3 and 1.4 must employ low-noise and low-power amplifiers, oscillators, and multipliers regardless of whether the actual communication is in analog or digital form. For example, a 20-μV signal (analog or digital) received by the antenna cannot be directly applied to a digital gate. Similarly, the video signal collectively captured by the pixels in a digital camera must be processed with low noise and distortion before it appears in the digital domain.

Second, digital circuits require analog expertise as the speed increases. Figure 1.8 exemplifies this point by illustrating two binary data waveforms, one at 100 Mb/s and another at 1 Gb/s. The finite risetime and falltime of the latter raises many issues in the operation of gates, flipflops, and other digital circuits, necessitating great attention to each point on the waveform.

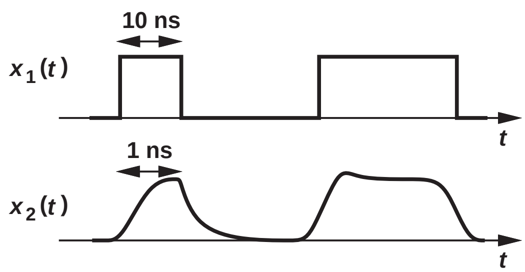


Figure 1.8 Data waveforms at 100 Mb/s and 1 Gb/s.

1.3 BASIC CONCEPTS*

Analysis of microelectronic circuits draws upon many concepts that are taught in basic courses on signals and systems and circuit theory. This section provides a brief review of these concepts so as to refresh the reader's memory and establish the terminology used throughout this book. The reader may first glance through this section to determine which topics need a review or simply return to this material as it becomes necessary later.

1.3.1 Analog and Digital Signals

An electric signal is a waveform that carries information. Signals that occur in nature can assume all values in a given range. Called "analog," such signals include voice, video, seismic, and music waveforms. Shown in Fig. 1.9(a), an analog voltage

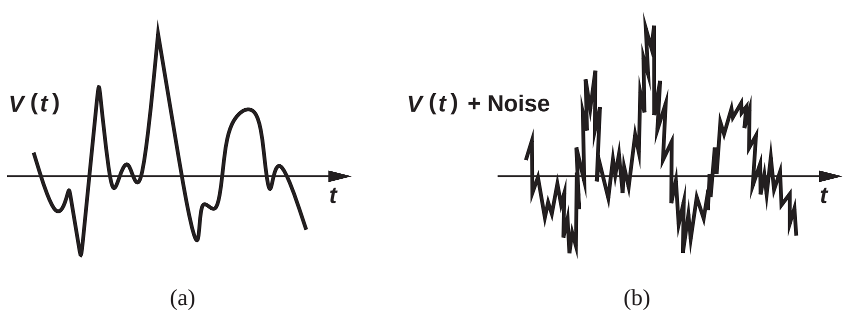


Figure 1.9 (a) Analog signal, (b) effect of noise on analog signal.

*This section serves as a review and can be skipped in classroom teaching.

waveform swings through a "continuum" of values and provides information at each instant of time.

While occurring all around us, analog signals are difficult to "process" due to sensitivities to such circuit imperfections as "noise" and "distortion."[5] As an example, Figure 1.9(b) illustrates the effect of noise. Furthermore, analog signals are difficult to "store" because they require "analog memories" (e.g., capacitors).

By contrast, a digital signal assumes only a finite number of values at only certain points in time. Depicted in Fig. 1.10(a) is a "binary" waveform, which remains at only one of two levels for each period, T. So long as the two voltages corresponding to ONEs and ZEROs differ sufficiently, logical circuits sensing such a signal process it correctly—even if noise or distortion create some corruption [Fig. 1.10(b)]. We therefore consider digital signals more "robust" than their analog counterparts. The storage of binary signals (in a digital memory) is also much simpler.

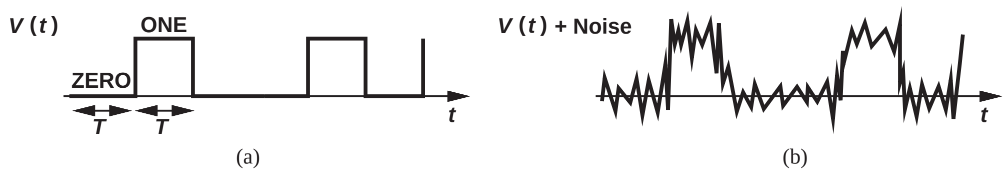


Figure 1.10 (a) Digital signal, (b) effect of noise on digital signal.

The foregoing observations favor processing of signals in the digital domain, suggesting that inherently analog information must be converted to digital form as early as possible. Indeed, complex microelectronic systems such as digital cameras, camcorders, and compact disk (CD) recorders perform some analog processing, "analog-to-digital conversion," and digital processing (Fig. 1.11), with the first two functions playing a critical role in the quality of the signal.

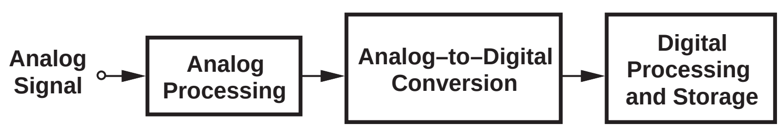


Figure 1.11 Signal processing in a typical system.

It is worth noting that many digital binary signals must be viewed and processed as analog waveforms. Consider, for example, the information stored on a hard disk in a computer. Upon retrieval, the "digital" data appears as a distorted waveform with only a few millivolts of amplitude (Fig. 1.12). Such a small separation between ONEs and ZEROs proves inadequate if this signal is to drive a logical gate, demanding a great deal of amplification and other analog processing before the data reaches a robust digital form.

[5]Distortion arises if the output is not a linear function of input.