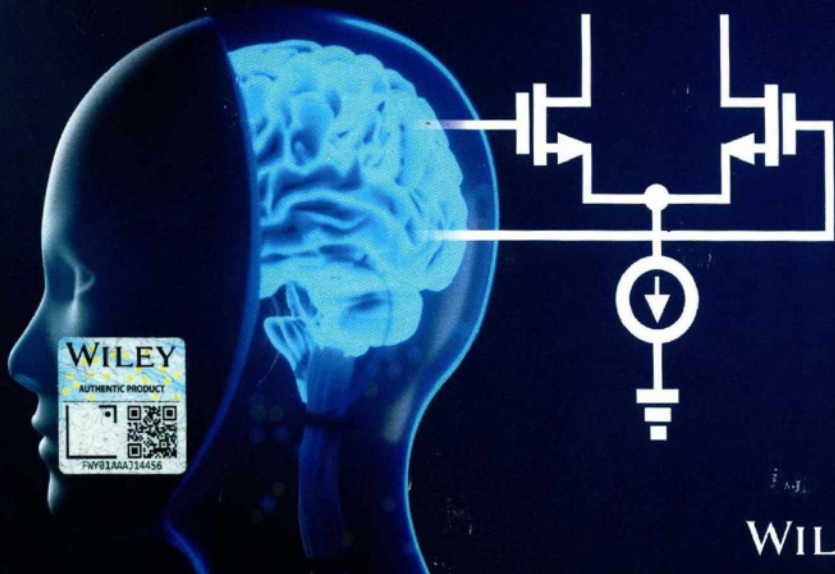


THIRD EDITION

FUNDAMENTALS OF MICROELECTRONICS

WITH ROBOTICS AND BIOENGINEERING APPLICATIONS

BEHZAD RAZAVI



Fundamentals of Microelectronics

with **Robotics** and **Bioengineering**
Applications

Third 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*.

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Preface to Third Edition

The second edition of this book was published seven years ago. Since then, I have been developing new materials that can enhance the readers' learning experience. In particular, the third edition is introduced with two significant additions:

Companion Videos Students generally prefer to watch a lecture before reading the related concepts in a book. With the proliferation of online videos, this preference has become so dominant that students rarely consider reading as their first option. I therefore began to ponder how this book could benefit from video lectures.

In 2014, I produced a video lecture series, called *Electronics 1*, that paralleled roughly the first nine chapters of the book. The series spanned 45 one-hour lectures recorded in front of a smart board, including segments called "Frontiers in Electronics," which highlighted real-life applications. The videos were posted on YouTube and quickly garnered a wide audience. This motivated me to develop another 45 lectures, called *Electronics 2*, to cover Chapters 10–12. The 90 lectures have been collectively viewed 3 million times and for a total of 500,000 hours. With thousands of positive messages that the viewers have sent me, I am convinced that the videos can serve as an effective means of learning for the readers of this book as well. The video titles and links are shown at the beginning of each chapter.

Robotics and Bioengineering Applications In addition to communications and computing, a number of other fields rely heavily on microelectronics. Chief among them are robotics and bioengineering. The principal challenge in teaching such applications in a fundamental electronics course is how to distill the concepts in a language that the students can appreciate. I have collected about two dozen robotics and bioengineering examples that portray the use of various electronic devices and circuits in real-life systems.

Another change in the third edition is that the end-of-chapter problems have been rearranged, and various typos have been corrected.

Behzad Razavi
September 2020

Preface to Second Edition

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 indispensable 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

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

Behzad Razavi