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Foundations of Analog and Digital Electronic Circuits

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MORGAN KAUFMANN

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AMSTERDAM • BOSTON • HEIDELBERG • LONDON
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SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO
MORGAN KAUFMANN PUBLISHERS IS AN IMPRINT OF ELSEVIER

MORGAN KAUFMANN PUBLISHERS

Publisher: Denise E. M. Penrose
Publishing Services Manager: Simon Crump
Editorial Assistant: Valerie Witte
Cover Design: Frances Baca
Composition: Cepha Imaging Pvt. Ltd., India
Technical Illustration: Dartmouth Publishing, Inc.
Copyeditor: Eileen Kramer
Proofreader: Katherine Hasal
Indexer: Kevin Broccoli
Interior printer: China Translation and Printing Services Ltd.
Cover printer: China Translation and Printing Services Ltd.

Morgan Kaufmann Publishers is an imprint of Elsevier.
500 Sansome Street, Suite 400, San Francisco, CA 94111

This book is printed on acid-free paper.

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Library of Congress Cataloging-in-Publication Data
ISBN: 1-55860-735-8

For information on all Morgan Kaufmann publications,
visit our Web site at www.mkp.com or www.books.elsevier.com

Printed in China
5 6 7 8 9 5 4 3 2 1

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In Praise of *Foundations of Analog and Digital Electronic Circuits*

"This book, crafted and tested with MIT sophomores in electrical engineering and computer science over a period of more than six years, provides a comprehensive treatment of both circuit analysis and basic electronic circuits. Examples such as digital and analog circuit applications, field-effect transistors, and operational amplifiers provide the platform for modeling of active devices, including large-signal, small-signal (incremental), nonlinear and piecewise-linear models. The treatment of circuits with energy-storage elements in transient and sinusoidal-steady-state circumstances is thorough and accessible. Having taught from drafts of this book five times, I believe that it is an improvement over the traditional approach to circuits and electronics, in which the focus is on analog circuits alone."

-PAUL E. GRAY, Massachusetts Institute of Technology

"My overall reaction to this book is overwhelmingly favorable. Well-written and pedagogically sound, the book provides a good balance between theory and practical application. I think that combining circuits and electronics is a very good idea. Most introductory circuit theory texts focus primarily on the analysis of lumped element networks without putting these networks into a practical electronics context. However, it is becoming more critical for our electrical and computer engineering students to understand and appreciate the common ground from which both fields originate."

-GARY MAY, Georgia Institute of Technology

"Without a doubt, students in engineering today want to quickly relate what they learn from courses to what they experience in the electronics-filled world they live in. Understanding today's digital world requires a strong background in analog circuit principles as well as a keen intuition about their impact on electronics. In Foundations... Agarwal and Lang present a unique and powerful approach for an exciting first course introducing engineers to the world of analog and digital systems."

-RAVI SUBRAMANIAN, Berkeley Design Automation

"Finally, an introductory circuit analysis book has been written that truly unifies the treatment of traditional circuit analysis and electronics. Agarwal and Lang skillfully combine the fundamentals of circuit analysis with the fundamentals of modern analog and digital integrated circuits. I applaud their decision to eliminate from their book the usual mandatory chapter on Laplace transforms, a tool no longer in use by modern circuit designers. I expect this book to establish a new trend in the way introductory circuit analysis is taught to electrical and computer engineers."

-TIM TRICK, University of Illinois at Urbana-Champaign

ABOUT THE AUTHORS

Anant Agarwal is Professor of Electrical Engineering and Computer Science at the Massachusetts Institute of Technology. He joined the faculty in 1988, teaching courses in circuits and electronics, VLSI, digital logic and computer architecture. Between 1999 and 2003, he served as an associate director of the Laboratory for Computer Science. He holds a Ph.D. and an M.S. in Electrical Engineering from Stanford University, and a bachelor's degree in Electrical Engineering from IIT Madras. Agarwal led a group that developed Sparcle (1992), a multithreaded microprocessor, and the MIT Alewife (1994), a scalable shared-memory multiprocessor. He also led the VirtualWires project at MIT and was a founder of Virtual Machine Works, Inc., which took the VirtualWires logic emulation technology to market in 1993. Currently Agarwal leads the Raw project at MIT, which developed a new kind of reconfigurable computing chip. He and his team were awarded a Guinness world record in 2004 for LOUD, the largest microphone array in the world, which can pinpoint, track and amplify individual voices in a crowd. Co-founder of Engim, Inc., which develops multi-channel wireless mixed-signal chipsets, Agarwal also won the Maurice Wilkes prize for computer architecture in 2001, and the Presidential Young Investigator award in 1991.

Jeffrey H. Lang is Professor of Electrical Engineering and Computer Science at the Massachusetts Institute of Technology. He joined the faculty in 1980 after receiving his SB (1975), SM (1977) and Ph.D. (1980) degrees from the Department of Electrical Engineering and Computer Science. He served as the Associate Director of the MIT Laboratory for Electromagnetic and Electronic Systems between 1991 and 2003, and as an Associate Editor of "Sensors and Actuators" between 1991 and 1994. Professor Lang's research and teaching interests focus on the analysis, design and control of electromechanical systems with an emphasis on rotating machinery, micro-scale sensors and actuators, and flexible structures. He has also taught courses in circuits and electronics at MIT. He has written over 170 papers and holds 10 patents in the areas of electromechanics, power electronics and applied control, and has been awarded four best-paper prizes from IEEE societies. Professor Lang is a Fellow of the IEEE, and a former Hertz Foundation Fellow.

Agarwal and Lang have been working together for the past eight years on a fresh approach to teaching circuits. For several decades, MIT had offered a traditional course in circuits designed as the first core undergraduate course in EE. But by the mid-'90s, vast advances in semiconductor technology, coupled with dramatic changes in students' backgrounds evolving from a ham radio to computer culture, had rendered this traditional course poorly motivated, and many parts of it were virtually obsolete. Agarwal and Lang decided to revamp and broaden this first course for EE, ECE or EECS by establishing a strong connection between the contemporary worlds of digital and analog systems, and by unifying the treatment of circuits and basic MOS electronics. As they developed the course, they solicited comments and received guidance from a large number of colleagues from MIT and other universities, students, and alumni, as well as industry leaders.

Unable to find a suitable text for their new introductory course, Agarwal and Lang wrote this book to follow the lecture schedule used in their course. "Circuits and Electronics" is taught in both the spring and fall semesters at MIT, and serves as a prerequisite for courses in signals and systems, digital/computer design, and advanced electronics. The course material is available worldwide on MIT's OpenCourseWare website, http://ocw.mit.edu/OcwWeb/index.htm.

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PREFACE

APPROACH

This book is designed to serve as a first course in an electrical engineering or an electrical engineering and computer science curriculum, providing students at the sophomore level a transition from the world of physics to the world of electronics and computation. The book attempts to satisfy two goals: Combine circuits and electronics into a single, unified treatment, and establish a strong connection with the contemporary worlds of both digital and analog systems.

These goals arise from the observation that the approach to introducing electrical engineering through a course in traditional circuit analysis is fast becoming obsolete. Our world has gone digital. A large fraction of the student population in electrical engineering is destined for industry or graduate study in digital electronics or computer systems. Even those students who remain in core electrical engineering are heavily influenced by the digital domain.

Because of this elevated focus on the digital domain, basic electrical engineering education must change in two ways: First, the traditional approach to teaching circuits and electronics without regard to the digital domain must be replaced by one that stresses the circuits foundations common to both the digital and analog domains. Because most of the fundamental concepts in circuits and electronics are equally applicable to both the digital and the analog domains, this means that, primarily, we must change the way in which we motivate circuits and electronics to emphasize their broader impact on digital systems. For example, although the traditional way of discussing the dynamics of first-order RC circuits appears unmotivated to the student headed into digital systems, the same pedagogy is exciting when motivated by the switching behavior of a switch and resistor inverter driving a non-ideal capacitive wire. Similarly, we motivate the study of the step response of a second-order RLC circuit by observing the behavior of a MOS inverter when pin parasitics are included.

Second, given the additional demands of computer engineering, many departments can ill-afford the luxury of separate courses on circuits and on electronics. Rather, they might be combined into one course.[1] Circuits courses

1. In his paper, "Teaching Circuits and Electronics to First-Year Students," in *Int. Symp. Circuits and Systems (ISCAS)*, 1998, Yannis Tsividis makes an excellent case for teaching an integrated course in circuits and electronics.

treat networks of passive elements such as resistors, sources, capacitors, and inductors. Electronics courses treat networks of both passive elements and active elements such as MOS transistors. Although this book offers a unified treatment for circuits and electronics, we have taken some pains to allow the crafting of a two-semester sequence — one focused on circuits and another on electronics — from the same basic content in the book.

Using the concept of "abstraction," the book attempts to form a bridge between the world of physics and the world of large computer systems. In particular, it attempts to unify electrical engineering and computer science as the art of creating and exploiting successive abstractions to manage the complexity of building useful electrical systems. Computer systems are simply one type of electrical system.

In crafting a single text for both circuits and electronics, the book takes the approach of covering a few important topics in depth, choosing more contemporary devices when possible. For example, it uses the MOSFET as the basic active device, and relegates discussions of other devices such as bipolar transistors to the exercises and examples. Furthermore, to allow students to understand basic circuit concepts without the trappings of specific devices, it introduces several abstract devices as examples and exercises. We believe this approach will allow students to tackle designs with many other extant devices and those that are yet to be invented.

Finally, the following are some additional differences from other books in this field:

- The book draws a clear connection between electrical engineering and physics by showing clearly how the lumped circuit abstraction directly derives from Maxwell's Equations and a set of simplifying assumptions.
- The concept of abstraction is used throughout the book to unify the set of engineering simplifications made in both analog and digital design.
- The book elevates the focus of the digital domain to that of analog. However, our treatment of digital systems emphasizes their analog aspects. We start with switches, sources, resistors, and MOSFETs, and apply KVL, KCL, and so on. The book shows that digital versus analog behavior is obtained by focusing on particular regions of device behavior.
- The MOSFET device is introduced using a progression of models of increased refinement — the S model, the SR model, the SCS model, and the SU model.
- The book shows how significant amounts of insight into the static and dynamic operation of digital circuits can be obtained with very simple models of MOSFETs.

- Various properties of devices, for example, the memory property of capacitors, or the gain property of amplifiers, are related to both their use in analog circuits and digital circuits.
- The state variable viewpoint of transient problems is emphasized for its intuitive appeal and since it motivates computer solutions of both linear or nonlinear network problems.
- Issues of energy and power are discussed in the context of both analog and digital circuits.
- A large number of examples are picked from the digital domain emphasizing VLSI concepts to emphasize the power and generality of traditional circuit analysis concepts.

With these features, we believe this book offers the needed foundation for students headed towards either the core electrical engineering majors — including digital and RF circuits, communication, controls, signal processing, devices, and fabrication — or the computer engineering majors — including digital design, architecture, operating systems, compilers, and languages.

MIT has a unified electrical engineering and computer science department. This book is being used in MIT's introductory course on circuits and electronics. This course is offered each semester and is taken by about 500 students a year.

OVERVIEW

Chapter 1 discusses the concept of abstraction and introduces the lumped circuit abstraction. It discusses how the lumped circuit abstraction derives from Maxwell's Equations and provides the basic method by which electrical engineering simplifies the analysis of complicated systems. It then introduces several ideal, lumped elements including resistors, voltage sources, and current sources.

This chapter also discusses two major motivations of studying electronic circuits — modeling physical systems and information processing. It introduces the concept of a model and discusses how physical elements can be modeled using ideal resistors and sources. It also discusses information processing and signal representation.

Chapter 2 introduces KVL and KCL and discusses their relationship to Maxwell's Equations. It then uses KVL and KCL to analyze simple resistive networks. This chapter also introduces another useful element called the dependent source.

Chapter 3 presents more sophisticated methods for network analysis.

Chapter 4 introduces the analysis of simple, nonlinear circuits.

Chapter 5 introduces the digital abstraction, and discusses the second major simplification by which electrical engineers manage the complexity of building large systems.[2]

Chapter 6 introduces the switch element and describes how digital logic elements are constructed. It also describes the implementation of switches using MOS transistors. Chapter 6 introduces the S (switch) and the SR (switch-resistor) models of the MOSFET and analyzes simple switch circuits using the network analysis methods presented earlier. Chapter 6 also discusses the relationship between amplification and noise margins in digital systems.

Chapter 7 discusses the concept of amplification. It presents the SCS (switch-current-source) model of the MOSFET and builds a MOSFET amplifier.

Chapter 8 continues with small signal amplifiers.

Chapter 9 introduces storage elements, namely, capacitors and inductors, and discusses why the modeling of capacitances and inductances is necessary in high-speed design.

Chapter 10 discusses first order transients in networks. This chapter also introduces several major applications of first-order networks, including digital memory.

Chapter 11 discusses energy and power issues in digital systems and introduces CMOS logic.

Chapter 12 analyzes second order transients in networks. It also discusses the resonance properties of RLC circuits from a time-domain point of view.

Chapter 13 discusses sinusoidal steady state analysis as an alternative to the time-domain transient analysis. The chapter also introduces the concepts of impedance and frequency response. This chapter presents the design of filters as a major motivating application.

Chapter 14 analyzes resonant circuits from a frequency point of view.

Chapter 15 introduces the operational amplifier as a key example of the application of abstraction in analog design.

Chapter 16 discusses diodes and simple diode circuits.

The book also contains appendices on trignometric functions, complex numbers, and simultaneous linear equations to help readers who need a quick refresher on these topics or to enable a quick lookup of results.

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2. The point at which to introduce the digital abstraction in this book and in a corresponding curriculum was arguably the topic over which we agonized the most. We believe that introducing the digital abstraction at this point in the course balances (a) the need for introducing digital systems as early as possible in the curriculum to excite and motivate students (especially with laboratory experiments), with (b) the need for providing students with enough of a toolchest to be able to analyze interesting digital building blocks such as combinational logic. Note that we recommend introduction of digital systems a lot sooner than suggested by Tsividis in his 1998 ISCAS paper, although we completely agree his position on the need to include some digital design.

COURSE ORGANIZATION

The sequence of chapters has been organized to suit a one or two semester integrated course on circuits and electronics. First and second order circuits are introduced as late as possible to allow the students to attain a higher level of mathematical sophistication in situations in which they are taking a course on differential equations at the same time. The digital abstraction is introduced as early as possible to provide early motivation for the students.

Alternatively, the following chapter sequences can be selected to organize the course around a circuits sequence followed by an electronics sequence. The circuits sequence would include the following: Chapter 1 (lumped circuit abstraction), Chapter 2 (KVL and KCL), Chapter 3 (network analysis), Chapter 5 (digital abstraction), Chapter 6 (S and SR MOS models), Chapter 9 (capacitors and inductors), Chapter 10 (first-order transients), Chapter 11 (energy and power, and CMOS), Chapter 12 (second-order transients), Chapter 13 (sinusoidal steady state), Chapter 14 (frequency analysis of resonant circuits), and Chapter 15 (operational amplifier abstraction — optional).

The electronics sequence would include the following: Chapter 4 (nonlinear circuits), Chapter 7 (amplifiers, the SCS MOSFET model), Chapter 8 (small-signal amplifiers), Chapter 13 (sinusoidal steady state and filters), Chapter 15 (operational amplifier abstraction), and Chapter 16 (diodes and power circuits).

WEB SUPPLEMENTS

We have gathered a great deal of material to help students and instructors using this book. This information can be accessed from the Morgan Kaufmann website:

www.mkp.com/companions/1558607358

The site contains:

- Supplementary sections and examples. We have used the icon WWW in the text to identify sections or examples.
- Instructor's manual
- A link to the MIT OpenCourseWare website for the authors' course, 6.002 Circuits and Electronics. On this site you will find:
  - Syllabus. A summary of the objectives and learning outcomes for course 6.002.
  - Readings. Reading assignments based on Foundations of Analog and Digital Electronic Circuits.
  - Lecture Notes. Complete set of lecture notes, accompanying video lectures, and descriptions of the demonstrations made by the instructor during class.

- Labs. A collection of four labs: Thevenin/Norton Equivalents and Logic Gates, MOSFET Inverting Amplifiers and First-Order Circuits, Second-Order Networks, and Audio Playback System. Includes an equipment handout and lab tutorial. Labs include pre-lab exercises, in-lab exercises, and post-lab exercises.
- Assignments. A collection of eleven weekly homework assignments.
- Exams. Two quizzes and a Final Exam.
- Related Resources. Online exercises in Circuits and Electronics for demonstration and self-study.

ACKNOWLEDGMENTS

These notes evolved out of an initial set of notes written by Campbell Searle for 6.002 in 1991. The notes were also influenced by several who taught 6.002 at various times including Steve Senturia and Gerry Sussman. The notes have also benefited from the insights of Steve Ward, Tom Knight, Chris Terman, Ron Parker, Dimitri Antoniadis, Steve Umans, David Perreault, Karl Berggren, Gerry Wilson, Paul Gray, Keith Carver, Mark Horowitz, Yannis Tsividis, Cliff Pollock, Denise Penrose, Greg Schaffer, and Steve Senturia. We are also grateful to our reviewers including Timothy Trick, Barry Farbrother, John Pinkston, Stephane Lafortune, Gary May, Art Davis, Jeff Schowalter, John Uyemura, Mark Jupina, Barry Benedict, Barry Farbrother, and Ward Helms for their feedback. The help of Michael Zhang, Thit Minn, and Patrick Maurer in fleshing out problems and examples; that of Jose Oscar Mur-Miranda, Levente Jakab, Vishal Kapur, Matt Howland, Tom Kotwal, Michael Jura, Stephen Hou, Shelley Duvall, Amanda Wang, Ali Shoeb, Jason Kim, Charvak Karpe and Michael Jura in creating an answer key; that of Rob Geary, Yu Xinjie, Akash Agarwal, Chris Lang, and many of our students and colleagues in proofreading; and that of Anne McCarthy, Cornelia Colyer, and Jennifer Tucker in figure creation is also gratefully acknowledged. We gratefully acknowledge Maxim for their support of this book, and Ron Koo for making that support possible, as well as for capturing and providing us with numerous images of electronic components and chips. Ron Koo is also responsible for encouraging us to think about capturing and articulating the quick, intuitive process by which seasoned electrical engineers analyze circuits — our numerous sections on intuitive analysis are a direct result of his encouragement. We also thank Adam Brand and Intel Corp. for providing us with the images of the Pentium IV.

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