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PREFACE TO THE FIRST EDITION

This volume is intended as an electronic circuit design textbook and reference book; it begins at a level suitable for those with no previous exposure to electronics and carries the reader through to a reasonable degree of proficiency in electronic circuit design. We have used a straightforward approach to the essential ideas of circuit design, coupled with an in-depth selection of topics. We have attempted to combine the pragmatic approach of the practicing physicist with the quantitative approach of the engineer, who wants a thoroughly evaluated circuit design.

This book evolved from a set of notes written to accompany a one-semester course in laboratory electronics at Harvard. That course has a varied enrollment – undergraduates picking up skills for their eventual work in science or industry, graduate students with a field of research clearly in mind, and advanced graduate students and post-doctoral researchers who suddenly find themselves hampered by their inability to “do electronics.”

It soon became clear that existing textbooks were inadequate for such a course. Although there are excellent treatments of each electronics specialty, written for the planned sequence of a four-year engineering curriculum or for the practicing engineer, those books that attempt to address the whole field of electronics seem to suffer from excessive detail (the handbook syndrome), from oversimplification (the cookbook syndrome), or from poor balance of material. Much of the favorite pedagogy of beginning textbooks is quite unnecessary and, in fact, is not used by practicing engineers, while useful circuitry and methods of analysis in daily use by circuit designers lie hidden in application notes, engineering journals, and hard-to-get data books. In other words, there is a tendency among textbook writers to represent the theory, rather than the art, of electronics.

We collaborated in writing this book with the specific intention of combining the discipline of a circuit design engineer with the perspective of a practicing experimental physicist and teacher of electronics. Thus, the treatment in this book reflects our philosophy that electronics, as currently practiced, is basically a simple art, a combination of some basic laws, rules of thumb, and a large bag of tricks. For these reasons we have omitted entirely the

usual discussions of solid-state physics, the *h*-parameter model of transistors, and complicated network theory, and reduced to a bare minimum the mention of load lines and the *s*-plane. The treatment is largely nonmathematical, with strong encouragement of circuit brainstorming and mental (or, at most, back-of-the-envelope) calculation of circuit values and performance.

In addition to the subjects usually treated in electronics books, we have included the following:

- an easy-to-use transistor model;
- extensive discussion of useful subcircuits, such as current sources and current mirrors;
- single-supply op-amp design;
- easy-to-understand discussions of topics on which practical design information is often difficult to find: op-amp frequency compensation, low-noise circuits, phase-locked loops, and precision linear design;
- simplified design of active filters, with tables and graphs;
- a section on noise, shielding, and grounding;
- a unique graphical method for streamlined low-noise amplifier analysis;
- a chapter on voltage references and regulators, including constant current supplies;
- a discussion of monostable multivibrators and their idiosyncrasies;
- a collection of digital logic pathology, and what to do about it;
- an extensive discussion of interfacing to logic, with emphasis on the new NMOS and PMOS LSI;
- a detailed discussion of A/D and D/A conversion techniques;
- a section on digital noise generation;
- a discussion of minicomputers and interfacing to data buses, with an introduction to assembly language;
- a chapter on microprocessors, with actual design examples and discussion – how to design them into instruments, and how to make them do what you want;
- a chapter on construction techniques: prototyping, printed circuit boards, instrument design;

- a simplified way to evaluate high-speed switching circuits;
- a chapter on scientific measurement and data processing: what you can measure and how accurately, and what to do with the data;
- bandwidth narrowing methods made clear: signal averaging, multichannel scaling, lock-in amplifiers, and pulse-height analysis;
- amusing collections of “bad circuits,” and collections of “circuit ideas”;
- useful appendixes on how to draw schematic diagrams, IC generic types, *LC* filter design, resistor values, oscilloscopes, mathematics review, and others;
- tables of diodes, transistors, FETs, op-amps, comparators, regulators, voltage references, microprocessors, and other devices, generally listing the characteristics of both the most popular and the best types.

Throughout we have adopted a philosophy of naming names, often comparing the characteristics of competing devices for use in any circuit, and the advantages of alternative circuit configurations. Example circuits are drawn with real device types, not black boxes. The overall intent is to bring the reader to the point of understanding clearly the choices one makes in designing a circuit – how to choose circuit configurations, device types, and parts values. The use of largely nonmathematical circuit design techniques does not result in circuits that cut corners or compromise performance or reliability. On the contrary, such techniques enhance one’s understanding of the real choices and compromises faced in engineering a circuit and represent the best approach to good circuit design.

This book can be used for a full-year electronic circuit design course at the college level, with only a minimum mathematical prerequisite; namely, some acquaintance with trigonometric and exponential functions, and preferably a bit of differential calculus. (A short review of complex numbers and derivatives is included as an appendix.) If the less essential sections are omitted, it can serve as the text for a one-semester course (as it does at Harvard).

A separately available laboratory manual, *Laboratory Manual for the Art of Electronics* (Horowitz and Robinson, 1981), contains twenty-three lab exercises, together with reading and problem assignments keyed to the text.

To assist the reader in navigation, we have designated with open boxes in the margin those sections within each chapter that we feel can be safely passed over in an abbreviated reading. For a one-semester course it would probably be wise to omit, in addition, the materials of Chapter 5 (first half), 7, 12, 13, 14, and possibly 15, as explained in the introductory paragraphs of those chapters.

We would like to thank our colleagues for their thoughtful comments and assistance in the preparation of the manuscript, particularly Mike Aronson, Howard Berg, Dennis Crouse, Carol Davis, David Griesinger, John Hagen, Tom Hayes, Peter Horowitz, Bob Kline, Costas Papaliolios, Jay Sage, and Bill Vetterling. We are indebted to Eric Hieber and Jim Mobley, and to Rhona Johnson and Ken Werner of Cambridge University Press, for their imaginative and highly professional work.

Paul Horowitz
Winfield Hill
April 1980

PREFACE TO THE SECOND EDITION

Electronics, perhaps more than any other field of technology, has enjoyed an explosive development in the last four decades. Thus it was with some trepidation that we attempted, in 1980, to bring out a definitive volume teaching the art of the subject. By “art” we meant the kind of mastery that comes from an intimate familiarity with real circuits, actual devices, and the like, rather than the more abstract approach often favored in textbooks on electronics. Of course, in a rapidly evolving field, such a nuts-and-bolts approach has its hazards – most notably a frighteningly quick obsolescence.

The pace of electronics technology did not disappoint us! Hardly was the ink dry on the first edition before we felt foolish reading our words about “the classic [2Kbyte] 2716 EPROM... with a price tag of about \$25.” They’re so classic you can’t even get them anymore, having been replaced by EEPROMs 64 times as large, and costing less than half the price! Thus a major element of this revision responds to improved devices and methods – completely rewritten chapters on microcomputers and microprocessors (using the IBM PC and the 68008) and substantially revised chapters on digital electronics (including PLDs, and the new HC and AC logic families), on op-amps and precision design (reflecting the availability of excellent FET-input op-amps), and on construction techniques (including CAD/CAM). Every table has been revised, some substantially; for example, in Table 4.1 (operational amplifiers) only 65% of the original 120 entries survived, with 135 new op-amps added.

We have used this opportunity to respond to readers’ suggestions and to our own experiences using and teaching from the first edition. Thus we have rewritten the chapter on FETs (it was too complicated) and repositioned it before the chapter on op-amps (which are increasingly of FET construction). We have added a new chapter on low-power and micropower design (both analog and digital), a field both important and neglected. Most of the remaining chapters have been extensively revised. We have added many new tables, including A/D and D/A converters, digital logic components, and low-power devices, and throughout the book we have expanded the number of figures. The

book now contains 78 tables (available separately as *The Horowitz and Hill Component Selection Tables*) and over 1000 figures.

Throughout the revision we have strived to retain the feeling of informality and easy access that made the first edition so successful and popular, both as reference and text. We are aware of the difficulty students often experience when approaching electronics for the first time: the field is densely interwoven, and there is no path of learning that takes you, by logical steps, from neophyte to broadly competent designer. Thus we have added extensive cross-referencing throughout the text; in addition, we have expanded the separate *Laboratory Manual* into a *Student Manual (Student Manual for The Art of Electronics)*, by Thomas C. Hayes and Paul Horowitz, complete with additional worked examples of circuit designs, explanatory material, reading assignments, laboratory exercises, and solutions to selected problems. By offering a student supplement, we have been able to keep this volume concise and rich with detail, as requested by our many readers who use the volume primarily as a reference work.

We hope this new edition responds to all our readers’ needs – both students and practicing engineers. We welcome suggestions and corrections, which should be addressed directly to Paul Horowitz, Physics Department, Harvard University, Cambridge, MA 02138.

In preparing this new edition, we are appreciative of the help we received from Mike Aronson and Brian Matthews (AOX, Inc.), John Greene (University of Cape Town), Jeremy Avigad and Tom Hayes (Harvard University), Peter Horowitz (EVI, Inc.), Don Stern, and Owen Walker. We thank Jim Mobley for his excellent copyediting, Sophia Prybylski and David Tranah of Cambridge University Press for their encouragement and professional dedication, and the never-sleeping typesetters at Rosenlau Publishing Services, Inc. for their masterful composition in *T_EX*.

Finally, in the spirit of modern jurisprudence, we remind you to read the legal notice here appended.

Paul Horowitz
Winfield Hill
March 1989

Legal notice

In this book we have attempted to teach the techniques of electronic design, using circuit examples and data that we believe to be accurate. However, the examples, data, and other information are intended solely as teaching aids and should not be used in any particular application without independent testing and verification by the person making the application. Independent testing and verification are especially important in any application in which incorrect functioning could result in personal injury or damage to property.

For these reasons, we make no warranties, express or implied, that the examples, data, or other infor-

mation in this volume are free of error, that they are consistent with industry standards, or that they will meet the requirements for any particular application. THE AUTHORS AND PUBLISHER EXPRESSLY DISCLAIM THE IMPLIED WARRANTIES OF MERCHANTABILITY AND OF FITNESS FOR ANY PARTICULAR PURPOSE, even if the authors have been advised of a particular purpose, and even if a particular purpose is indicated in the book. The authors and publisher also disclaim all liability for direct, indirect, incidental, or consequential damages that result from any use of the examples, data, or other information in this book.

PREFACE TO THE THIRD EDITION

Moore's Law continues to assert itself, unabated, since the publication of the second edition a quarter century ago. In this new third (and final!) edition we have responded to this upheaval with major enhancements:

- an emphasis on devices and circuits for *A/D* and *D/A conversion* (Chapter 13), because embedded microcontrollers are everywhere
- illustration of specialized peripheral ICs for use with microcontrollers (Chapter 15)
- detailed discussions of logic family choices, and of interfacing logic signals to the real world (Chapters 10 and 12)
- greatly expanded treatment of important topics in the essential analog portion of instrument design:
 - precision circuit design (Chapter 5)
 - low-noise design (Chapter 8)
 - power switching (Chapters 3, 9, and 12)
 - power conversion (Chapter 9)

And we have added many entirely new topics, including:

- digital audio and video (including cable and satellite TV)
- transmission lines
- circuit simulation with SPICE
- transimpedance amplifiers
- depletion-mode MOSFETs
- protected MOSFETs
- high-side drivers
- quartz crystal properties and oscillators
- a full exploration of JFETs
- high-voltage regulators
- optoelectronics
- power logic registers
- delta-sigma converters
- precision multislope conversion
- memory technologies
- serial buses
- illustrative “Designs by the Masters”

In this new edition we have responded, also, to the reality that previous editions have been enthusiastically embraced by the community of practicing circuit designers, even though *The Art of Electronics* (now 35 years in print) originated as a course textbook. So we've continued the “how we do it” approach to circuit design; and we've ex-

panded the depth of treatment, while (we hope) retaining the easy access and explanation of basics. At the same time we have split off some of the specifically course-related teaching and lab material into a separate *Learning the Art of Electronics* volume, a substantial expansion of the previous edition's companion *Student Manual for The Art of Electronics*.¹

Digital oscilloscopes have made it easy to capture, annotate, and combine measured waveforms, a capability we have exploited by including some 90 'scope screenshots illustrating the behavior of working circuits. Along with those doses of reality, we have included (in tables and graphs) substantial quantities of highly useful measured data – such as transistor noise and gain characteristics (e_n , i_n , r_{bb} ; h_{fe} , g_m , g_{oss}), analog switch characteristics (R_{ON} , Q_{inj} , capacitance), op-amp input and output characteristics (e_n and i_n over frequency, input common-mode range, output swing, auto-zero recovery, distortion, available packages), and approximate prices (!) – the sort of data often buried or omitted in datasheets but which you need (and don't have the time to measure) when designing circuits.

We've worked diligently, over the 20 years it has taken to prepare this edition, to include important circuit design information, in the form of some 350 graphs, 50 photographs, and 87 tables (listing more than 1900 active components), the last enabling intelligent choice of circuit components by listing essential characteristics (both specified and measured) of available parts.

Because of the significant expansion of topics and depth of detail, we've had to leave behind some topics that were treated in the second edition,² notwithstanding the use of larger pages, more compact fonts, and most figures sized to fit in a single column. Some additional related material that we had hoped to include in this volume (on real-world properties of components, and advanced topics in BJTs, FETs, op-amps, and power control) will instead be published in a forthcoming companion volume, *The Art*

¹ Both by Hayes, T. and Horowitz, P., Cambridge University Press, 1989 and 2016.

² Which, however, will continue to be available as an e-book.