教育部高等教育司推荐
国外优秀信息科学与技术系列教学用书

数字设计

——原理与实践

（第三版 影印版）

DIGITAL DESIGN

Principles & Practices

(Third Edition)

■ John F. Wakerly

高等教育出版社
Higher Education Press
Pearson Education
出版集团

教育部高等教育司推荐
国外优秀信息科学与技术系列教学用书

数字设计

——原理与实践

（第三版　影印版）

DIGITAL DESIGN

Principles and Practices

(Third Edition)

John F. Wakerly

高等教育出版社
Pearson Education 出版集团

图字：01-2001-1042 号

Digital Design: Principles and Practices, 3rd ed.
By John F. Wakerly

图书在版编目(CIP)数据

数字设计：原理与实践：英文 /（美）韦克利（Wakerly,J.F.) —3 版.
—北京：高等教育出版社，2001
ISBN 7-04-010042-8

I. 数… II. 韦… III. 数字电路–电路设计–英文
IV.TN711.52

中国版本图书馆 CIP 数据核字（2001）第 19782 号

数字设计——原理与实践（第三版）
John F. Wakerly

出版发行	高等教育出版社		
社　　址	北京市东城区沙滩后街55号	邮政编码	100009
电　　话	010-64054588	传　　真	010-64014048
网　　址	http:// www. hep. edu. cn http:// www. hep. com. cn		
经　　销	新华书店北京发行所		
印　　刷	北京民族印刷厂		
开　　本	787×1092　1/16	版　　次	2001 年 5 月第 3 版
印　　张	60.75	印　　次	2001 年 5 月第 1 次印刷
字　　数	1 358 000	定　　价	49.50 元

前　言

20世纪末，以计算机和通信技术为代表的信息科学和技术，对世界的经济、军事、科技、教育、文化、卫生等方面的发展产生了深刻的影响，由此而兴起的信息产业已经成为世界经济发展的支柱。进入21世纪，各国为了加快本国的信息产业，加大了资金投入和政策扶持。

为了加快我国信息产业的进程，在我国《国民经济和社会发展第十个五年计划纲要》中，明确提出“以信息化带动工业化，发挥后发优势，实现社会生产力的跨越式发展。”信息产业的国际竞争将日趋激烈。在我国加入WTO后，我国信息产业将面临国外竞争对手的严峻挑战。竞争成败最终将取决于信息科学和技术人才的多少与优劣。

在20世纪末，我国信息产业虽然得到迅猛发展，但与国际先进国家相比，差距还很大。为了赶上并超过国际先进水平，我国必须加快信息技术人才的培养，特别要培养一大批具有国际竞争能力的高水平的信息技术人才，促进我国信息产业和国家信息化水平的全面提高。为此，教育部高等教育司根据教育部吕福源副部长的意见，在长期重视推动高等学校信息科学和技术的教学的基础上，将实施超前发展战略，采取一些重要举措，加快推动高等学校的信息科学和技术等相关专业的教学工作。在大力宣传、推荐我国专家编著的面向21世纪和“九五”重点的信息科学和技术课程教材的基础上，在有条件的高等学校的某些信息科学和技术课程中推动使用国外优秀教材的影印版进行英语或双语教学，以缩短我国在计算机教学上与国际先进水平的差距，同时也有助于强化我国大学生的英语水平。

为了达到上述目的，在分析一些出版社已影印相关教材，一些学校已试用影印教材进行教学的基础上，教育部高等教育司组织并委托高等教育出版社开展国外优秀信息科学和技术优秀教材及其教学辅助材料的引进研究与影印出版的试点工作。为推动用影印版教材进行教学创造条件。

本次引进的系列教材的影印出版工作，是在对我国高校的信息科学和技术专业的课程与美国高校的进行对比分析的基础上展开的；所影印出版的教材均由我国主要高

校的信息科学和技术专家组成的专家组，从国外近两年出版的大量最新教材中精心筛选评审通过的内容新、有影响的优秀教材；影印教材的定价原则上应与我国大学教材价格相当。

教育部高等教育司将此影印系列教材推荐给高等学校，希望有关教师选用，使用后有什么意见和建议请及时反馈。也希望有条件的出版社，根据影印教材的要求，积极参加此项工作，以便引进更多、更新、更好的外国教材和教学辅助材料。

同时，感谢国外有关出版公司对此项引进工作的配合，欢迎更多的国外公司关心并参与此项工作。

教育部高等教育司
二〇〇一年四月

To my teachers

FOREWORD

Moore's Law, which observes that semiconductor technology advances exponentially, has been valid for over three decades. Experts predict it will continue to hold for at least one more. When integrated circuits were introduced, logic packages had a dozen or so transistors. Today, with exponential increases in circuit density, microprocessor chips have passed the 10-million-transistor mark. In less than another decade they will reach 100 million transistors per chip.

To keep up with Moore's Law, design techniques have changed drastically. Hand-crafted logic circuits were once the norm. Now designers generate circuits from high-level descriptions. Connections on printed-circuit boards have been absorbed within chips. With programmable logic, on-chip logic functions and connections can be updated within the user environment.

How does education keep up with Moore's Law? What can we do to enable students to practice their skills today and adapt them tomorrow to new generations of devices? This is the challenge John Wakerly faced when he began this work.

His approach is multifaceted. It is grounded in basic principles of digital design that do not change with technology, such as combinational logic, sequential logic, and state machines. Wakerly weds these principles with tools and practical techniques that teach how to design for today's technology. These include how to use the ABEL and VHDL design languages, how to structure designs with large building blocks, and how to implement designs with programmable logic devices. These techniques are essential for successful design.

The most difficult goal is to help the student adapt to the inevitable changes to come. Wakerly does this by revealing what is happening underneath the logic. For example, he gives transistor models of gates and uses them to expose issues related to timing and noise. Gates may become faster and denser and may use different control voltages, but how to assure correct and reliable operation will be a continuing concern. We learn the characteristics, constraints, and failure modes and how to design to them. We learn through examples of alternate designs how to judge design quality and evaluate tradeoffs. As new technology emerges, we will be able to design to it.

Wakerly enhances the approach with presentation skills that are rare in college texts. The reader will quickly appreciate the effective graphics, entertaining writing style, and instructive exercises.

Moore's Law condemns textbooks in this field to short lives. Nevertheless, Wakerly's text is a classic.

Harold S. Stone
Princeton, New Jersey

PREFACE

This book is for everyone who wants to design and build real digital circuits. It is based on the idea that, in order to do this, you have to grasp the fundamentals, but at the same time you need to understand how things work in the real world. Hence, the "principles and practices" theme.

introductory courses

electronics concepts

The material in this book is appropriate for introductory courses on digital logic design in electrical or computer engineering or computer science curricula. Computer science students who are unfamiliar with basic electronics concepts or who just aren't interested in the electrical behavior of digital devices may wish to skip Chapter 3; the rest of the book is written to be independent of this material as much as possible. On the other hand, *anyone* with a basic electronics background who wants to get up to speed on digital electronics can do so by reading Chapter 3. In addition, students with *no* electronics background can get the basics by reading Bruce M. Fleischer's "Electrical Circuits Review," a freely reproducible 20-page electronics tutorial available on this book's Web site, `www.ddpp.com`.

optional sections

Although this book's level is introductory, it contains much more material than can be taught in a typical introductory course. Once I started writing, I found that I had many important things to say that wouldn't fit into a one-quarter course at Stanford or a 400-page book. Therefore, I have followed my usual practice of including *everything* that I think is at least moderately important, and leaving it up to the instructor or reader to decide what is most important in a particular environment. To help these decisions along, though, I've marked the headings of *optional sections* with an asterisk. In general, these sections can be skipped without any loss of continuity in the non-optional sections that follow.

advanced courses

laboratory courses

fun stuff

Undoubtedly, some people will use this book in advanced courses and in laboratory courses. Advanced students will want to skip the basics and get right into the fun stuff. Once you know the basics, the most important and fun stuff in this book is in the sections on hardware description languages ABEL and VHDL, where you'll discover that your programming courses actually helped prepare you to design hardware.

working digital designers

Another use of this book is as a self-study reference for a working digital designer, who may be either of two kinds:

Novice If you're just getting started as a working digital designer, and you took a very "theoretical" logic design course in school, you should concentrate on Chapters 3, 5, 6, and 8–11 to get prepared for the real world.

Old pro If you're experienced, you may not need all of the "practices" material in this book, but the principles in Chapters 2, 4, and 7 can help you organize your thinking, and the discussions there of what's important and what's not might relieve the guilt you feel for not having used a Karnaugh map in 10 years. The examples in Chapters 6, 8, and 9 should give you additional insights into and appreciation for a variety of design methods. Finally, the ABEL and VHDL language descriptions and examples sprinkled throughout Chapters 4 through 9 may serve as your first organized introduction to HDL-based design.

marginal notes
marginal pun

All readers should make good use of the comprehensive index and of the *marginal notes* throughout the text that call attention to definitions and important topics. Maybe the highlighted topics in *this* section were more marginal than important, but I just wanted to show off my text formatting system.

Chapter Descriptions

What follows is a list of short descriptions of this book's eleven chapters and appendix. This may remind you of the section in software guides, "For People Who Hate Reading Manuals." If you read this list, then maybe you don't have to read the rest of the book.

- Chapter 1 gives a few basic definitions and lays down the ground rules for what we think is and is not important in this book.
- Chapter 2 is an introduction to binary number systems and codes. Readers who are already familiar with binary number systems from a software course should still read Sections 2.10–2.13 to get an idea of how binary codes are used by hardware. Advanced students can get a nice introduction to error-detecting codes by reading Sections 2.14 and 2.15. The material in Section 2.16.1 should be read by everyone; it is used in some design examples in Chapter 8.
- Chapter 3 describes "everything you ever wanted to know about" digital circuit operation, placing primary emphasis on the external electrical characteristics of logic devices. The starting point is a basic electronics background including voltage, current, and Ohm's law; readers unfamiliar

with these concepts may wish to consult the "Electrical Circuits Review" mentioned earlier. This chapter may be omitted by readers who aren't interested in how to make real circuits work, or who have the luxury of having someone else to do the dirty work.

- Chapter 4 teaches combinational logic design principles, including switching algebra and combinational-circuit analysis, synthesis, and minimization. Introductions to ABEL and VHDL appear at the end of this chapter.
- Chapter 5 begins with a discussion of digital-system documentation standards, probably the most important practice for aspiring designers to start practicing. Next, this chapter introduces programmable logic devices (PLDs), focusing on their capability to realize combinational logic functions. The rest of the chapter describes commonly used combinational logic functions and applications. For each function, it describes standard MSI building blocks, ABEL programs for PLD realizations, and VHDL models.
- Chapter 6 is a collection of larger combinational-circuit design examples. For each example, it shows how the design can be carried out with MSI building blocks (if appropriate), ABEL and PLDs, or VHDL that can be targeted to a CPLD or FPGA.
- Chapter 7 teaches sequential logic design principles, starting with latches and flip-flops. The main emphasis in this chapter is on the analysis and design of clocked synchronous state machines. However, for the brave and daring, the chapter includes an introduction to fundamental-mode circuits and the analysis and design of feedback sequential circuits. The chapter ends with sections on ABEL and VHDL features that support sequential-circuit design.
- Chapter 8 is all about the practical design of sequential circuits. Like Chapter 5 before it, this chapter focuses on commonly used functions and gives examples using MSI building blocks, ABEL and PLDs, and VHDL. Sections 8.8 and 8.9 discuss the inevitable impediments to the ideal of fully synchronous design and address the important problem of how to live synchronously in an asynchronous world.
- Chapter 9 is a collection of state-machine and larger sequential-circuit design examples. Each example is carried out both using ABEL for a PLD and using VHDL that can be targeted to a CPLD or FPGA.
- Chapter 10 is an introduction to memory devices, CPLDs, and FPGAs. Memory coverage includes read-only memory and static and dynamic read-write memories from the points of view of both internal circuitry and functional behavior. The last two sections introduce CPLD and FPGA architecture.

Errors

Waming: This book may contain errors. The author assumes no liability for any damage—incidental, brain, or otherwise—caused by errors.

There, that should make the lawyers happy. Now, to make *you* happy, let me assure you that a great deal of care has gone into the preparation of this manuscript to make it as error free as possible. I am anxious to learn of the remaining errors so that they may be fixed in future printings, editions, and spin-offs. Therefore I will pay $5 to the first finder of each undiscovered error, be it technical, typographical, or otherwise. Please email your comments by using the link on the Web site, or by writing to me at `john@wakerly.com`.

Any reader can obtain an up-to-date list of discovered errors using the link at the book's Web site. It will be a very short file transfer, I hope.

Acknowledgements

Many people helped make this book possible. Most of them helped with the first and second editions and are acknowledged there. Preparation of the third edition has been a lonelier task, but it was made easier by my colleagues Mario Mazzola and Prem Jain at Cisco Systems. They and the company made it possible for me to cut back my commitment at Cisco to less than half time for the eight months that it took to prepare this edition.

For the ideas on the "principles" side of this book, I still owe great thanks to my teacher, research advisor, and friend Ed McCluskey. On the "practices" side, my personal "Digital Designers Hall of Fame" includes (in chronological order): Ed Davidson, Jim McClure, Courtenay Heater, Sam Wood, Curt Widdoes, Prem Jain, Ted Tracy, Dave Raaum, Akhil Duggal, Des Young, and Tom Edsall.

The seed that got me started writing this book and many others was planted in the early 70s by Harold Stone at Stanford. He put me to work reviewing and indexing his books, and his computer organization books inspired me to write my first software book. Now, I'd like to offer Harold my belated thanks for getting me started, and I give him special thanks for helping to pad out this edition by another two pages!

In the summer of 1997, during the early stages of this edition's planning, friend and colleague Jean-Pierre Steger took a sabbatical from the Burgdorf School of Engineering near Bern, Switzerland to help me get jump-started with VHDL, the Xilinx Foundation tools, and other topics. A number of other people contributed review comments or other materials to this edition, including John Birkner, Rebecca Farley, Don Gaubatz, John Gill, Linley Gwennap, Jesse Jenkins, and Jeff Purnell.

Xilinx, Inc. naturally deserves credit for providing the Foundation tools that are an important adjunct to this edition. On the people side, their original

University Program leader Jason Feinsmith was very helpful, and their recently appointed leader Patrick Kane has supported our efforts enthusiastically.

Since the second edition was published, I have received many helpful comments from readers. In addition to suggesting or otherwise motivating many improvements, readers have spotted dozens of typographical and technical errors whose fixes are incorporated in this third edition.

My sponsoring editor at Prentice Hall, Tom Robbins, deserves great thanks for his patience. He's the second editor to have been lured to Prentice Hall in part by the (falsely attractive) prospect of working on a project with me, only to find out upon his arrival that the project was very late. In Tom's case, though, I had known him since the early 80s when he first tried to sign me up for a project with another publisher, and we'd been trying to find a way to work together ever since. We're finally there, starting the third decade of our friendship. Tom contributed more than patience—among other things, you have him to thank for getting you the free Xilinx software at the back of this book (most printings).

Production editor Irwin Zucker also deserves credit for providing a very smooth interface with the production side of the house and for putting in long hours to help me during the final "crunch" stage of the project. If not for him, I would not be able to leave on a long-planned three-week family vacation later this morning. (I'm told that if I hadn't finished in time, our 90-pound dog would have gone to Europe in my seat instead!) Robert Lentz also did a great job as a copy editor which I could live with :-) .

Special thanks go to artist Robert McFadden, whose trippy cover painting is hanging in my home along with several other of his far-out works. His painting, which I commissioned and he completed well over a year ago, provided me with the motivation to actually get the *inside* of the book done.

It seems like some disaster always strikes just as I am completing one of these projects. For the first edition, it was the World-Series earthquake of 1989. For the second edition, it was surgery four days before the book's completion for a ruptured and very yucky-looking appendix. This time, I seemed to have dodged the bullet so far. Actually, I won't be completely done until I've finished the index, which I'll be preparing on my laptop as we ride the rails through Europe over the next few weeks. Let's hope I don't forget it on some train!

As always, I must thank my wife Kate for putting up with the late hours, frustration, crabbiness, preoccupation, and phone calls from weird people that occur when I'm engaged in a writing project like this. We hope you enjoy starting this book as much as we enjoy finishing it!

John F. Wakerly
Mountain View, California

CONTENTS