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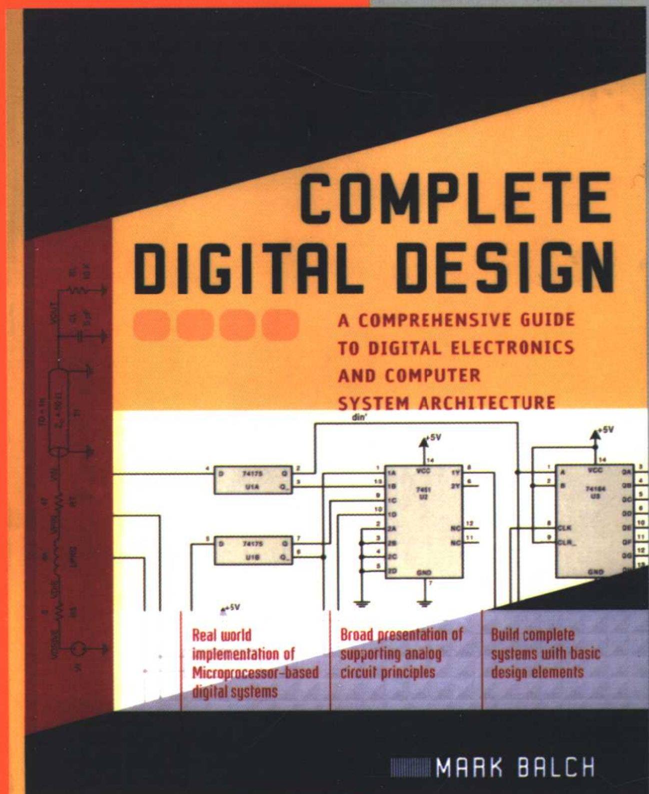
Mark Balch

完整的数字设计



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国外大学优秀教材——微电子类系列（影印版）

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Complete Digital Design

Mark Balch

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北京

Mark Balch
Complete Digital Design
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出版前言

微电子技术是信息科学技术的核心技术之一，微电子产业是当代高新技术产业群的核心和维护国家主权、保障国家安全的战略性产业。我国在《信息产业“十五”计划纲要》中明确提出：坚持自主发展，增强创新能力和核心竞争力，掌握以集成电路和软件技术为重点的信息产业的核心技术，提高具有自主知识产权产品的比重。发展集成电路技术的关键之一是培养具有国际竞争力的专业人才。

微电子技术发展迅速，内容更新快，而我国微电子专业图书数量少，且内容和体系不能反映科技发展的水平，不能满足培养人才的需求，为此，我们系统挑选了一批国外经典教材和前沿著作，组织分批出版。图书选择的几个基本原则是：在本领域内广泛采用，有很大影响力；内容反映科技的最新发展，所述内容是本领域的研究热点；编写和体系与国内现有图书差别较大，能对我国微电子教育改革有所启示。本套丛书还侧重于微电子技术的实用性，选取了一批集成电路设计方面的工程技术用书，使读者能方便地应用于实践。本套丛书不仅能作为相关课程的教科书和教学参考书，也可作为工程技术人员的自学读物。

我们真诚地希望，这套丛书能对国内高校师生、工程技术人员以及科研人员的学习和工作有所帮助，对推动我国集成电路的发展有所促进。也衷心期望着广大读者对我们一如既往的关怀和支持，鼓励我们出版更多、更好的图书。

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Complete Digital Design

A Comprehensive Guide to Digital Electronics and Computer System Architecture

影 印 版 序

现代高性能通信和嵌入式系统的蓬勃发展对于电子工程师和大学生的数字电路硬件设计技术提出了新的挑战和要求。一方面为了使所设计的数字系统能成功地工作，设计人员不仅需要具备系统原理方面的基础知识，而且也需要在具体实现数字设计的专门知识方面有一个全面的理解和指导。另一方面，一个完整的现代数字系统不仅包括数据处理和运算，也包括数据的通讯和交换；不仅包括数字信号，也包括模拟信号以及在数模信号之间的相互转换。因此作为一个成熟的数字系统设计的专业技术人员以及希望在这一当前最活跃领域奉献和成功的大学生和研究生应当从实现系统的角度来获取各种电子部件和模块的基本知识以及它们相互间的有机联系。《完整的数字设计》（Complete Digital Design）一书正是出于这两个方面的考虑和读者的实际需要应运而生。

本书作者 Mark Balch 是在美国硅谷长期从事高性能计算机网络硬件设计并积极参与工业标准制定的资深工程师，有丰富的实际工作经验和对数字设计的深刻理解；他负责设计过许多通信、HDTV、工业计算机、家电等领域的电子产品包括 PCB、FPGA 和专用集成电路。作者在这些成功经验及对数字系统设计与实现深刻理解基础上所著的这本书能帮助读者理解和探索数字系统的整体结构、定义数字系统的全定制设计要求、研究模块和元件相互间的密切联系、评估现有的设计部件和技术并帮助解决具体的设计问题，其中包括以微处理器为基础的数字系统设计、支持数字系统的模拟电路原理以及如何用基本的设计元件和最新的设计技术实现一个完整的数字系统。本书内容丰富、覆盖面广。正如书名本身表明的那样，这是一本名副其实内容完整的数字系统设计教科书，也是一本任何时候都应用方便的电子设计实用参考书。

全书分四部分：（1）数字逻辑和微处理器基础（基本的存储和通讯技术）。（2）先进的计算机结构和逻辑设计，包括现代微处理器结构、逻辑设计方法、高性能存储器和网络技术以及可编程逻辑器件。（3）实现完整数字系统所需要的关键模拟支持电路，包括集成电路元件、运算放大器、数模和模数转换电路和数据转换技术。（4）在联系前三部分的基础上讨论实际的数字设计问题包括时钟分配，电源电压调节、信号完整性、可测性设计以及电路制造技术。各部分既相互联系，又相对独立。因此本书既可以按顺序阅读，又可以单独参考，书后并有附录列出丰富的参考资料，为进一步探索和实际设计提供方便。

本书可作为本科生和研究生数字逻辑类课程及其延伸课程的教科书，也可作为数字设计和实践课程的指导书。由于本书紧密联系设计实践和实际的电子产品及厂商，书中并有许多内容很少在以往正式的基本电子学课程中讨论，因此本书对于改变目前国内这方面实践课程缺乏，电子工程设计“软化”的状况无疑是“雪中送炭”。本书由于覆盖面广，各部分有机联系，可以使许多从事实际工作的设计人员不必去补习或复习高深的基础就可以起步设计现时先进的数字电子系统，也不必从“海量”材料中苦心寻觅和费力筛选出自己所需要的设计信息，因此本书也十分适用于专业工程技术人员、初次跨入数字设计领域的毕业生，甚至业余爱好者。

周润德
2003 年 11 月
于清华大学

PREFACE

Digital systems are created to perform data processing and control tasks. What distinguishes one system from another is an architecture tailored to efficiently execute the tasks for which it was designed. A desktop computer and an automobile's engine controller have markedly different attributes dictated by their unique requirements. Despite these differences, they share many fundamental building blocks and concepts. Fundamental to digital system design is the ability to choose from and apply a wide range of technologies and methods to develop a suitable system architecture. Digital electronics is a field of great breadth, with interdependent topics that can prove challenging for individuals who lack previous hands-on experience in the field.

This book's focus is explaining the real-world implementation of complete digital systems. In doing so, the reader is prepared to immediately begin design and implementation work without being left to wonder about the myriad ancillary topics that many texts leave to independent and sometimes painful discovery. A complete perspective is emphasized, because even the most elegant computer architecture will not function without adequate supporting circuits.

A wide variety of individuals are intended to benefit from this book. The target audiences include

- *Practicing electrical engineers seeking to sharpen their skills in modern digital system design.* Engineers who have spent years outside the design arena or in less-than-cutting-edge areas often find that their digital design skills are behind the times. These professionals can acquire directly relevant knowledge from this book's practical discussion of modern digital technologies and design practices.
- *College graduates and undergraduates seeking to begin engineering careers in digital electronics.* College curricula provide a rich foundation of theoretical understanding of electrical principles and computer science but often lack a practical presentation of how the many pieces fit together in real systems. Students may understand conceptually how a computer works while being incapable of actually building one on their own. This book serves as a bridge to take readers from the theoretical world to the everyday design world where solutions must be complete to be successful.
- *Technicians and hobbyists seeking a broad orientation to digital electronics design.* Some people have an interest in understanding and building digital systems without having a formal engineering degree. Their need for practical knowledge in the field is as strong as for degreed engineers, but their goals may involve laboratory support, manufacturing, or building a personal project.

There are four parts to this book, each of which addresses a critical set of topics necessary for successful digital systems design. The parts may be read sequentially or in arbitrary order, depending on the reader's level of knowledge and specific areas of interest.

A complete discussion of digital logic and microprocessor fundamentals is presented in the first part, including introductions to basic memory and communications architectures. More advanced computer architecture and logic design topics are covered in Part 2, including modern microprocessor architectures, logic design methodologies, high-performance memory and networking technologies, and programmable logic devices.

Part 3 steps back from the purely digital world to focus on the critical analog support circuitry that is important to any viable computing system. These topics include basic DC and AC circuit analysis, diodes, transistors, op-amps, and data conversion techniques. The fundamental topics from the first three parts are tied together in Part 4 by discussing practical digital design issues, including clock distribution, power regulation, signal integrity, design for test, and circuit fabrication techniques. These chapters deal with nuts-and-bolts design issues that are rarely covered in formal electronics courses.

More detailed descriptions of each part and chapter are provided below.

PART 1 DIGITAL FUNDAMENTALS

The first part of this book provides a firm foundation in the concepts of digital logic and computer architecture. Logic is the basis of computers, and computers are intrinsically at the heart of digital systems. We begin with the basics: logic gates, integrated circuits, microprocessors, and computer architecture. This framework is supplemented by exploring closely related concepts such as memory and communications that are fundamental to any complete system. By the time you have completed Part 1, you will be familiar with exactly how a computer works from multiple perspectives: individual logic gates, major architectural building blocks, and the hardware/software interface. You will also have a running start in design by being able to thoughtfully identify and select specific off-the-shelf chips that can be incorporated into a working system. A multilevel perspective is critical to successful systems design, because a system architect must simultaneously consider high-level feature trade-offs and low-level implementation possibilities. Focusing on one and not the other will usually lead to a system that is either impractical (too expensive or complex) or one that is not really useful.

Chapter 1, "Digital Logic," introduces the fundamentals of Boolean logic, binary arithmetic, and flip-flops. Basic terminology and numerical representations that are used throughout digital systems design are presented as well. On completing this chapter, the awareness gained of specific logical building blocks will help provide a familiarity with supporting logic when reading about higher-level concepts in later chapters.

Chapter 2, "Integrated Circuits and the 7400 Logic Families," provides a general orientation to integrated circuits and commonly used logic ICs. This chapter is where the rubber meets the road and the basics of logic design become issues of practical implementation. Small design examples provide an idea of how various logic chips can be connected to create functional subsystems. Attention is paid to readily available components and understanding IC specifications, without which chips cannot be understood and used. The focus is on design with real off-the-shelf components rather than abstract representations on paper.

Chapter 3, "Basic Computer Architecture," cracks open the heart of digital systems by explaining how computers and microprocessors function. Basic concepts, including instruction sets, memory, address decoding, bus interfacing, DMA, and assembly language, are discussed to create a complete picture of what a computer is and the basic components that go into all computers. Questions are not left as exercises for the reader. Rather, each mechanism and process in a basic computer is discussed. This knowledge enables you to move ahead and explore the individual concepts in more depth while maintaining an overall system-level view of how everything fits together.

Chapter 4, "Memory," discusses this cornerstone of digital systems. With the conceptual understanding from Chapter 3 of what memory is and the functions that it serves, the discussion progresses to explain specific types of memory devices, how they work, and how they are applicable to different computing applications. Trade-offs of various memory technologies, including SRAM, DRAM, flash, and EPROM, are explored to convey an understanding of why each technology has its place in various systems.

Chapter 5, "Serial Communications," presents one of the most basic aspects of systems design: moving data from one system to another. Without data links, computers would be isolated islands. Communication is key to many applications, whether accessing the Internet or gathering data from a remote sensor. Topics including RS-232 interfaces, modems, and basic multinode networking are discussed with a focus on implementing real data links.

Chapter 6, "Instructive Microprocessors and Microcomputer Elements," walks through five examples of real microprocessors and microcontrollers. The devices presented are significant because of their trail-blazing roles in defining modern computing architecture, as exhibited by the fact that, decades later, they continue to turn up in new designs in one form or another. These devices are used as vehicles to explain a wide range of computing issues from register, memory, and bus architectures to interrupt vectoring and operating system privilege levels.

PART 2 ADVANCED DIGITAL SYSTEMS

Digital systems operate by acquiring data, manipulating that data, and then transferring the results as dictated by the application. Part 2 builds on the foundations of Part 1 by exploring the state of the art in microprocessor, memory, communications, and logic implementation technologies. To effectively conceive and implement such systems requires an understanding of what is possible, what is practical, and what tools and building blocks exist with which to get started. On completing Parts 1 and 2, you will have acquired a broad understanding of digital systems ranging from small microcontrollers to 32-bit microcomputer architecture and high-speed networking, and the logic design methodologies that underlie them all. You will have the ability to look at a digital system, whether pre-existing or conceptual, and break it into its component parts—the first step in solving a problem.

Chapter 7, "Advanced Microprocessor Concepts," discusses the key architectural topics behind modern 32- and 64-bit computing systems. Basic concepts including RISC/CISC, floating-point arithmetic, caching, virtual memory, pipelining, and DSP are presented from the perspective of what a digital hardware engineer needs to know to understand system-wide implications and design useful circuits. This chapter does not instruct the reader on how to build the fastest microprocessors, but it does explain how these devices operate and, more importantly, what system-level design considerations and resources are necessary to achieve a functioning system.

Chapter 8, "High-Performance Memory Technologies," presents the latest SDR/DDR SDRAM and SDR/DDR/QDR SSRAM devices, explains how they work and why they are useful in high-performance digital systems, and discusses the design implications of each. Memory is used by more than just microprocessors. Memory is essential to communications and data processing systems. Understanding the capabilities and trade-offs of such a central set of technologies is crucial to designing a practical system. Familiarity with all mainstream memory technologies is provided to enable a firm grasp of the applications best suited to each.

Chapter 9, "Networking," covers the broad field of digital communications from a digital hardware perspective. Network protocol layering is introduced to explain the various levels at which hardware and software interact in modern communication systems. Much of the hardware responsibility for networking lies at lower levels in moving bits onto and off of the communications medium. This chapter focuses on the low-level details of twisted-pair and fiber-optic media, transceiver technologies, 8B10B channel coding, and error detection with CRC and checksum logic. A brief presentation of Ethernet concludes the chapter to show how a real networking standard functions.

Chapter 10, "Logic Design and Finite State Machines," explains how to implement custom logic to make a fully functional system. Most systems use a substantial quantity of off-the-shelf logic products to solve the problem at hand, but almost all require some custom support logic. This chapter begins by presenting hardware description languages, and Verilog in particular, as an efficient means of designing synchronous and combinatorial logic. Once the basic methodology of designing logic has been discussed, common support logic solutions, including address decoding, control/status registers, and interrupt control logic, are shown with detailed design examples. Designing logic to handle asynchronous inputs across multiple clock domains is presented with specific examples. More complex logic circuits capable of implementing arbitrary algorithms are built from finite state machines—a topic explored in detail with design examples to ensure that the concepts are properly translated into reality. Finally, state machine optimization techniques, including pipelining, are discussed to provide an understanding of how to design logic that can be reliably implemented.

Chapter 11, "Programmable Logic Devices," explains the various logic implementation technologies that are used in a digital system. GALs, PALs, CPLDs, and FPGAs are presented from the perspectives of how they work, how they are used to implement arbitrary logic designs, and the capabilities and features of each that make them suitable for various types of designs. These devices represent the glue that holds some systems together and the core operational elements of others. This chapter aids in deciding which technology is best suited to each logic application and how to select the right device to suit a specific need.

PART 3 ANALOG BASICS FOR DIGITAL SYSTEMS

All electrical systems are collections of analog circuits, but digital systems masquerade as discrete binary entities when they are properly designed. It is necessary to understand certain fundamental topics in circuit analysis so that digital circuits can be made to behave in the intended binary manner. Part 3 addresses many essential analog topics that have direct relevance to designing successful digital systems. Many digital engineers shrink away from basic DC and AC circuit analysis either for fear of higher mathematics or because it is not their area of expertise. This needn't be the case, because most day-to-day analysis required for digital systems can be performed with basic algebra. Furthermore, a digital systems slant on analog electronics enables many simplifications that are not possible in full-blown analog design. On completing this portion of the book, you will be able to apply passive components, discrete diodes and transistors, and op-amps in ways that support digital circuits.

Chapter 12, "Electrical Fundamentals," addresses basic DC and AC circuit analysis. Resistors, capacitors, inductors, and transformers are explained with straightforward means of determining voltages and currents in simple analog circuits. Nonideal characteristics of passive components are discussed, which is a critical aspect of modern, high-speed digital systems. Many a digital system has failed because its designers were unaware of increasingly nonideal behavior of components as operating frequencies get higher. Frequency-domain analysis and basic filtering are presented to explain common analog structures and how they can be applied to digital systems, especially in minimizing noise, a major contributor to transient and hard-to-detect problems.

Chapter 13, "Diodes and Transistors," explains the basic workings of discrete semiconductors and provides specific and fully analyzed examples of how they are easily applied to digital applications. LEDs are covered as well as bipolar and MOS transistors. An understanding of how diodes and transistors function opens up a great field of possible solutions to design problems. Diodes are essential in power-regulation circuits and serve as voltage references. Transistors enable electrical loads to be driven that are otherwise too heavy for a digital logic chip to handle.

Chapter 14, "Operational Amplifiers," discusses this versatile analog building block with many practical applications in digital systems. The design of basic amplifiers and voltage comparators is offered with many examples to illustrate all topics presented. All examples are thoroughly analyzed in a step-by-step process so that you can learn to use op-amps effectively on your own. Op-amps are useful in data acquisition and interface circuits, power supply and voltage monitoring circuits, and for implementing basic amplifiers and filters. This chapter applies the basic AC analysis skills explained previously in designing hybrid analog/digital circuits to support a larger digital system.

Chapter 15, "Analog Interfaces for Digital Systems," covers the basics of analog-to-digital and digital-to-analog conversion techniques. Many digital systems interact with real-world stimuli including audio, video, and radio frequencies. Data conversion is a key portion of these systems, enabling continuous analog signals to be represented and processed as binary numbers. Several common means of performing data conversion are discussed along with fundamental concepts such as the Nyquist frequency and anti-alias filtering.

PART 4 DIGITAL SYSTEM DESIGN IN PRACTICE

When starting to design a new digital system, high-profile features such as the microprocessor and memory architecture often get most of the attention. Yet there are essential support elements that may be overlooked by those unfamiliar with them and unaware of the consequences of not taking time to address necessary details. All too often, digital engineers end up with systems that almost work. A microprocessor may work properly for a few hours and then quit. A data link may work fine one day and then experience inexplicable bit errors the next day. Sometimes these problems are the result of logic bugs, but mysterious behavior may be related to a more fundamental electrical flaw. The final part of this book explains the supporting infrastructure and electrical phenomena that must be understood to design and build reliable systems.

Chapter 16, "Clock Distribution," explores an essential component of all digital systems: proper generation and distribution of clocks. Many common clock generation and distribution methods are presented with detailed circuit implementation examples including low-skew buffers, termination, and PLLs. Related subjects, including frequency synthesis, DLLs, and source-synchronous clocking, are presented to lend a broad perspective on system-level clocking strategies.

Chapter 17, "Voltage Regulation and Power Distribution" discusses the fundamental power infrastructure necessary for system operation. An introduction to general power handling is provided that covers issues such as circuit specifications and safety issues. Thermal analysis is emphasized for safety and reliability concerns. Basic regulator design with discrete components and integrated circuits is explained with numerous illustrative circuits for each topic. The remainder of the chapter addresses power distribution topics including wiring, circuit board power planes, and power supply decoupling capacitors.

Chapter 18, "Signal Integrity," delves into a set of topics that addresses the nonideal behavior of high-speed digital signals. The first half of this chapter covers phenomena that are common causes of corrupted digital signals. Transmission lines, signal reflections, crosstalk, and a wide variety of termination schemes are explained. These topics provide a basic understanding of what can go wrong and how circuits and systems can be designed to avoid signal integrity problems. Electromagnetic radiation, grounding, and static discharge are closely related subjects that are presented in the second half of the chapter. An overview is presented of the problems that can arise and their possible solutions. Examples illustrate concepts that apply to both circuit board design and overall system enclosure design—two equally important matters for consideration.

Chapter 19, "Designing for Success," explores a wide range of system-level considerations that should be taken into account during the product definition and design phases of a project. Component selection and circuit fabrication must complement the product requirements and available development and manufacturing resources. Often considered mundane, these topics are discussed because a successful outcome hinges on the availability and practicality of parts and technologies that are designed into a system. System testability is emphasized in this chapter from several perspectives, because testing is prominent in several phases of product development. Test mechanisms including boundary scan (JTAG), specific hardware features, and software diagnostic routines enable more efficient debugging and fault isolation in both laboratory and assembly line environments. Common computer-aided design software for digital systems is presented with an emphasis on Spice analog circuit simulation. Spice applications are covered and augmented by complete examples that start with circuits, proceed with Spice modeling, and end with Spice simulation result analysis. The chapter closes with a brief overview of common test equipment that is beneficial in debugging and characterizing digital systems.

Following the main text is Appendix A, a brief list of recommended resources for further reading and self-education. Modern resources range from books to trade journals and magazines to web sites.

Many specific vendors and products are mentioned throughout this book to serve as examples and as starting points for your exploration. However, there are many more companies and products than can be practically listed in a single text. Do not hesitate to search out and consider manufacturers not mentioned here, because the ideal component for your application might otherwise lie undiscovered. When specific components are described in this book, they are described in the context of the discussion at hand. References to component specifications cannot substitute for a vendor's data sheet, because there is not enough room to exhaustively list all of a component's attributes, and such specifications are always subject to revision by the manufacturer. Be sure to contact the manufacturer of a desired component to get the latest information on that product. Component manufacturers have a vested interest in providing you with the necessary information to use their products in a safe and effective manner. It is wise to take advantage of the resources that they offer. The widespread use of the Internet has greatly simplified this task.

True proficiency in a trade comes with time and practice. There is no substitute for experience or mentoring from more senior engineers. However, help in acquiring this experience by being pointed in the right direction can not only speed up the learning process, it can make it more enjoyable as well. With the right guide, a motivated beginner's efforts can be more effectively channeled through the early adoption of sound design practices and knowing where to look for necessary information. I sincerely hope that this book can be your guide, and I wish you the best of luck in your endeavors.

Mark Balch

ACKNOWLEDGMENTS

On completing a book of this nature, it becomes clear to the author that the work would not have been possible without the support of others. I am grateful for the many talented engineers that I have been fortunate to work with and learn from over the years. More directly, several friends and colleagues were kind enough to review the initial draft, provide feedback on the content, and bring to my attention details that required correction and clarification. I am indebted to Rich Chernock and Ken Wagner, who read through the entire text over a period of many months. Their thorough inspection provided welcome and valuable perspectives on everything ranging from fine technical points to overall flow and style. I am also thankful for the comments and suggestions provided by Todd Goldsmith and Jim O'Sullivan, who enabled me to improve the quality of this book through their input.

I am appreciative of the cooperation provided by several prominent technology companies. Mentor Graphics made available their ModelSim Verilog simulator, which was used to verify the correctness of certain logic design examples. Agilent Technologies, Fairchild Semiconductor, and National Semiconductor gave permission to reprint portions of their technical literature that serve as examples for some of the topics discussed.

Becoming an electrical engineer and, consequently, writing this book was spurred on by my early interest in electronics and computers that was fully supported and encouraged by my family. Whether it was the attic turned into a laboratory, a trip to the electronic supply store, or accompaniment to the science fair, my family has always been behind me.

Finally, I haven't sufficient words to express my gratitude to my wife Laurie for her constant emotional support and for her sound all-around advice. Over the course of my long project, she has helped me retain my sanity. She has served as editor, counselor, strategist, and friend. Laurie, thanks for being there for me every step of the way.

ABOUT THE AUTHOR

Mark Balch is an electrical engineer in the Silicon Valley who designs high-performance computer-networking hardware. His responsibilities have included PCB, FPGA, and ASIC design. Prior to working in telecommunications, Mark designed products in the fields of HDTV, consumer electronics, and industrial computers.

In addition to his work in product design, Mark has actively participated in industry standards committees and has presented work at technical conferences. He has also authored magazine articles on topics in hardware and system design. Mark holds a bachelor's degree in electrical engineering from The Cooper Union in New York City.

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