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# Digital System Design with Verilog and VHDL, Second Edition

# 数字系统设计

## (Verilog & VHDL版)(第二版)

## (英文版)


[美] Enoch O. Hwang 著

阎 波 朱晓章 姚 毅 改编



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## 内容简介

随着微电子技术与计算机技术的飞速发展，以及先进的电子设计自动化（EDA）技术及现场可编程门阵列（FPGA）器件的广泛应用，现代数字逻辑电路与系统的设计理念及实现技术已经发生了翻天覆地的变化。本书以微处理器系统作为复杂数字逻辑系统的代表，在简要介绍其工作原理的基础上，以CPU硬件结构框图为线索贯穿各个章节，详细讲述了如何构建基本组合/时序逻辑元件、如何利用已有元件组建数据通路与控制单元部件、如何利用已有部件实现一个通用CPU，以及如何通过进一步添加简单的输入输出接口来最终搭建出一个完整的微处理器系统。

本书脉络清晰、结构完整，通过在简单的数字逻辑元件与复杂的实用数字逻辑系统之间搭建桥梁，能够帮助读者深刻理解数字逻辑组件的设计与使用方法，进而全面和清晰地把握复杂数字系统的EDA设计与实现技术要点。本书及相关网站提供了丰富的实用学习资源，所有设计示例都提供了电路图以及Verilog与VHDL源码。

本书非常适合作为电子信息与通信、计算机、微电子、自动控制、仪器仪表等领域中数字电路与系统设计、计算机组成原理等相关课程的双语教学教材，也可供相关领域工程师作为实用设计的参考用书。



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# 导　读[①]

在应用需求的不断推进下，集成电路设计技术与工艺水平不断提高，高性能、低功耗的超大规模集成电路设计已成为电子信息与通信工程、计算机科学与工程、微电子科学与工程、控制科学与工程等众多领域里的战略性、前瞻性关键技术。如果您恰好已经或者即将进入这些应用领域，肯定已经意识到现代复杂数字系统设计方法与先进EDA实现技术的重要性和必要性，而这本书正是帮助您掌握相关入门知识的最佳之选。下面就让我们一起来一窥本书。

众所周知，虽然数字逻辑设计的基本原理始终如一，但数字电路与系统的开发与实现技术已随着现代VLSI设计方法学、先进EDA工具以及高性能FPGA器件的广泛应用发生了巨大的变化。目前许多与数字逻辑设计及实现技术有关的书籍要么仍然停留在“门级设计原理+标准组合/时序元件实现”的基础层面，要么直接进入“VLSI设计原理+EDA实现技术”的高级层面。这种技术层面的割裂可能导致（使用基础读物的）读者无法想象标准数字元件的真实应用场景与设计目标，譬如：我为什么需要一个计数器？我到底需要一个什么样的计数器？……而另一些（使用高级读物的）读者则可能一直被类似这样的问题困扰：用HDL语言实现的计数器与用C语言实现的计数器到底有什么不同？为什么我的计数器综合前仿真结果和综合后仿真结果看起来差别这么大？这些读者可能始终没能建立真正的硬件思维或者说根本还没有意识到自己是在设计硬件。

万幸的是，您手里这本书的主要目标正是力图填补简单数字逻辑元件与复杂实用数字逻辑系统之间的空白。本书以微处理器系统作为复杂数字逻辑系统的代表，在简要介绍其工作原理的基础上，详细讲述了如何构建基本组合/时序逻辑元件、如何利用基本逻辑元件组建数据通路与控制单元部件、如何利用已有部件实现一个通用CPU，以及如何通过进一步添加简单的输入输出接口来最终搭建出一个完整的微处理器系统。本书以每章开头的CPU硬件设计框图为线索，将基本原理、标准模块、复杂部件、实用系统有机地串接在一起，脉络清晰、结构完整，能够帮助读者全面了解和把握面向FPGA应用的数字逻辑系统EDA设计与实现技术要点。

本书及配套网站提供了很多有趣的例子，并给出了完整的硬件电路原理图及Verilog和VHDL代码，以便于读者亲自动手实践，籍此感受最先进EDA技术的便捷性和实用性。不过，书中的Verilog和VHDL代码均以独立小节的方式进行编排，所以如果只想了解数字逻辑电路的基本设计原则，那么也可以跳过这些内容而不必担心会失去连续性。

本书非常适合用作数字逻辑电路与系统设计的入门或实训参考教材，其主要内容安排如下。

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① 采用本书作为教材的授课教师，可按照书末所附表格，申请获取教学辅助资源。——编者注

**第1章　微处理器简介**。以微处理器电路为例，简要介绍了复杂数字系统的设计组成、设计层次以及EDA实现技术和HDL语言。

**第2章　数字电路基础**。介绍了数值进制和布尔代数，以及门电路、真值表等与数字逻辑设计相关的基本概念，并给出了一个简单汽车安全控制系统的电路设计及其Verilog/VHDL描述形式。

**第3章　组合电路**。介绍了组合电路的分析和设计（综合与优化）方法、竞争与冒险，并给出了一个LED显示译码器的设计及其Verilog/VHDL描述形式。

**第4章　标准组合元件**。介绍了ALU、译码器、比较器、多路复用器等常用较大规模标准组合元件的传统设计过程，以及EDA设计方法和Verilog/VHDL描述。这些元件将在后面用于构建微处理器中的数据通路。

**第5章　时序电路**。在介绍基本存储元件（触发器和锁存器）的基础上给出了寄存器文件和存储器，以及移位寄存器、计数器的设计方法及其Verilog/VHDL描述形式。

**第6章　有限状态机**。在第4章和第5章的基础上介绍了FSM的传统分析与设计（综合与优化）方法，并给出了几个实际设计示例及其Verilog/VHDL描述形式。FSM将在后面用于构建微处理器中的控制单元。

**第7章　定制微处理器**。在分析数据通路及控制单元设计需求的基础上，利用“有限状态机（FSM）+数据通路（Datapath）”的架构设计并实现了一个定制微处理器。

**第8章　通用微处理器**。在第7章的基础上讨论了两个简单通用微处理器（自定义指令集）的完整设计与构造，以及如何在其上执行机器语言程序。本章和本书的重点是，这两个功能齐全的通用微处理器可以用硬件实现，并由它们执行程序。

**第9章　微处理器接口**。提供了微处理器与真实外部设备之间最简单接口（LED显示屏及键盘）的完整示例。

强烈建议读者边学边做，能够看到自己设计的微处理器以真实硬件存在并能控制真实世界的外部设备，将是一种非常令人兴奋的体验，这不仅能帮助您真正领会本书的内容，而且能为您打开一扇更丰富多彩的数字设计技术之门。

本书由电子科技大学的3位老师改编，并将在电子科技大学格拉斯哥学院作为本科Application and Design of Digital Logic（数字逻辑应用与设计）课程教材。

# PREFACE

This book is about the digital logic design of microprocessors, and is intended to provide both an understanding of the basic principles of digital logic design, and how these fundamental principles are applied in the building of complex microprocessor circuits using current technologies. Although the basic principles of digital logic design have not changed, the design process and the implementation of the circuits have. With the advances in fully integrated modern hardware computer-aided design (CAD) tools for logic synthesis, simulation, and the implementation of digital circuits in field-programmable gate arrays (FPGAs), it is now possible to design and implement complex digital circuits very easily and quickly.

Many excellent books on digital logic design have followed the traditional approach of introducing the basic principles and theories of digital logic design and the building of separate standard combinational and sequential components. However, students are left to wonder about the purpose of these individual components and how they are used in the building of more complex digital circuits, such as microcontrollers and microprocessors that are used in controlling real-world electronic devices. The primary goal of this book is to fill in this gap by going beyond the logic principles and the building of basic standard components. The book discusses in detail how the basic components are combined together to form datapaths, how control units are designed, and how these two main components (datapath and control unit) are connected together to produce actual dedicated custom microprocessors and general-purpose microprocessors. The book ends with an entire chapter containing many examples on how microprocessors are interfaced with real-world devices.

Many texts on digital logic design and implementation techniques mainly focus on the logic gate level. At this low level, it is difficult to discuss larger and more complex circuits that are beyond the standard combinational and sequential circuits. However, with the introduction of the register-transfer technique for designing datapaths and the concept of a finite-state machine for control units, we can easily design a dedicated microprocessor for any arbitrary algorithm and then implement it on a FPGA chip to execute that algorithm. The book uses an easy-to-understand ground-up approach with complete circuit diagrams, and both Verilog and VHDL codes, starting with the building of basic digital components. These components are then used in the building of more complex components, and finally the building of the complete dedicated microprocessor circuit. The construction of a general-purpose microprocessor then comes naturally as a generalization of a dedicated microprocessor. At the end, students will have a complete understanding of how to design, construct, and implement fully working custom microprocessors.

# Design of Circuits using Verilog and VHDL[①]

Although this book provides coverage on both Verilog and VHDL for all of the circuits, this information can be omitted entirely while gaining an understanding of digital circuits and their design. For an introductory course in digital logic design, learning the basic principles is more important than learning how to use a hardware description language (HDL). In fact, instructors may find that students can get lost in learning the principles while trying to learn the language at the same time. With this in mind, the Verilog and VHDL code in the text is totally independent of the presentation of each topic and may be skipped without any loss of continuity.

On the other hand, by studying the HDL codes, the student can not only learn the use of a hardware description language but also learn how digital circuits can be designed automatically using a synthesizer. This book provides an introduction to both Verilog and VHDL and uses the "learn-by-examples" approach. In writing either Verilog or VHDL code at the dataflow and behavioral levels, the student will see the power and usefulness of a state-of-the-art hardware CAD synthesis tool.

# New to This Edition

In this newly revised second edition, a new chapter on interfacing microprocessors with external devices has been added. Just knowing how to design and implement a microprocessor is not sufficient. The main purpose and usage of a microprocessor is to control external devices. This entire chapter contains many real-world examples on interfacing microprocessors with external devices. Students can use these examples to help them in doing their final projects.

Throughout the book, many new examples have been added and old examples updated. This new edition also covers the usage of both Verilog and VHDL, the two industry standard hardware description languages for describing digital circuits. All circuit examples, in addition to having schematic diagrams, also include codes written in both VHDL and Verilog.

Using either the Altera or the Xilinx FPGA development software and their respective FPGA hardware development boards, students can actually implement these microprocessor circuits and see them execute, both in software simulation and in hardware. The book contains many interesting examples with complete schematic diagrams and Verilog and VHDL codes for implementing them in hardware. With the hands-on exercises, students will learn not only the principles of digital logic design but, also in practice, how circuits are implemented using current technologies.

To actually see your own microprocessor come to life in real hardware and being able to control real-world external devices is an exciting experience. Hopefully, this will help students to not only remember what they have learned but will also get them interested in the world of microprocessor controllers and digital circuit design.

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# Using This Book

This book can be used in either an introductory or a more advanced course in digital logic design. For an introductory course with no previous background in digital logic, Chapters 1 and 2 are intended to provide the fundamental basic concepts in digital logic design, while Chapters 3 and 4 cover the design of combinational circuits and standard combinational components. Chapter 5 on the design of sequential circuits can be introduced and lightly covered.

An advanced digital logic design course will start with sequential circuits in Chapter 5, and the design of finite-state machines in Chapter 6. Chapters 7 and 8 cover the design of datapaths and control units, and the building of dedicated and general-purpose microprocessors. Finally, Chapter 9 concludes with the interfacing of microprocessors with the external world.

It is strongly recommended that a lab component be fully integrated with the lecture. With an integrated lab, students can have a hands-on learning experience alongside the theoretical concepts that they have learned in class. In fact, many teachers find that too often not enough hours are given to the lab. As we probably know, it is often easier to understand the theory, but to actually implement a circuit and to get it to work requires much more detail and time. Ready-to-use labs that complement the lecture are available for download from the teachers' resource website at https://login.cengage.com.

**Chapter 1—Introduction to Microprocessor Design** gives an overview of the various components of a microprocessor circuit and the different abstraction levels in which digital circuits can be designed.

**Chapter 2—Fundamentals of Digital Circuits** provides the basic principles and theories for designing digital logic circuits by introducing binary numbers, the use of truth tables, Boolean algebra, and how the theories get translated into logic gates and circuit diagrams. Also a brief introduction to Verilog and VHDL is given.

**Chapter 3—Combinational Circuits** shows how combinational circuits are analyzed, synthesized, and optimized.

**Chapter 4—Standard Combinational Components** discusses the standard combinational components that are used as building blocks for larger digital circuits. These components include the adder, subtractor, arithmetic logic unit, decoder, multiplexer, tri-state buffer, comparator, shifter, and multiplier. In a hierarchical design, these components will be used in the building of the datapath used in the microprocessor.

**Chapter 5—Sequential Circuits** introduces latches and flip-flops as basic storage elements and then continues with larger storage components such as registers, register files, and memories. Special sequential components such as shift registers and counters are also covered.

**Chapter 6—Finite-State Machines** shows how finite-state machines are analyzed, synthesized, and optimized.

**Chapter 7—Dedicated Microprocessors** first introduces the need for a datapath, and then explains how a control unit, in the form of a finite-state machine, is used to control the datapath. The chapter expands further showing how dedicated microprocessors are constructed by connecting the datapath and the control unit together as one coherent circuit.

**Chapter 8—General-Purpose Microprocessors** continues on from Chapter 7 to suggest that a general-purpose microprocessor is really a dedicated microprocessor that is dedicated to only read, decode, and execute instructions. The chapter discusses the complete design and construction of two simple general-purpose microprocessors with their own custom instruction set, and how programs written in machine language are executed on them. The highlight of this chapter and this book is that these two fully-working general-purpose microprocessors can be implemented in hardware and have programs executed by them.

**Chapter 9—Interfacing Microprocessors** provides several complete examples on how to interface microprocessors with real-world external devices.

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I also want to thank my school, La Sierra University in sunny California, for giving me the time off to be at Zhejiang University and to work on this book. It would have been extremely difficult without this extra time.

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*Enoch O. Hwang, Ph.D.*
Riverside, California

# ABOUT THE AUTHOR

***Enoch Hwang*** has a Ph.D. in Computer Science from the University of California, Riverside. He is currently a professor of computer science at La Sierra University in Southern California teaching digital logic and microprocessor design. In 2015, he was invited as a visiting professor to Zhejiang University in Hangzhou, China, where he taught their Digital Systems Design course. Many new ideas from that class have been incorporated into this edition of the book.

Even from his childhood days, he has been fascinated with electronic circuits. In one of his first experiments, he attempted to connect a microphone to the speaker inside a portable radio through the earphone plug. Instead of hearing sound from the microphone through the speaker, smoke was seen coming out of the radio. Thus ended that experiment and his family's only radio. He now continues his interest in digital circuits with research in embedded microprocessor systems, controller automation, power optimization, and robotics.

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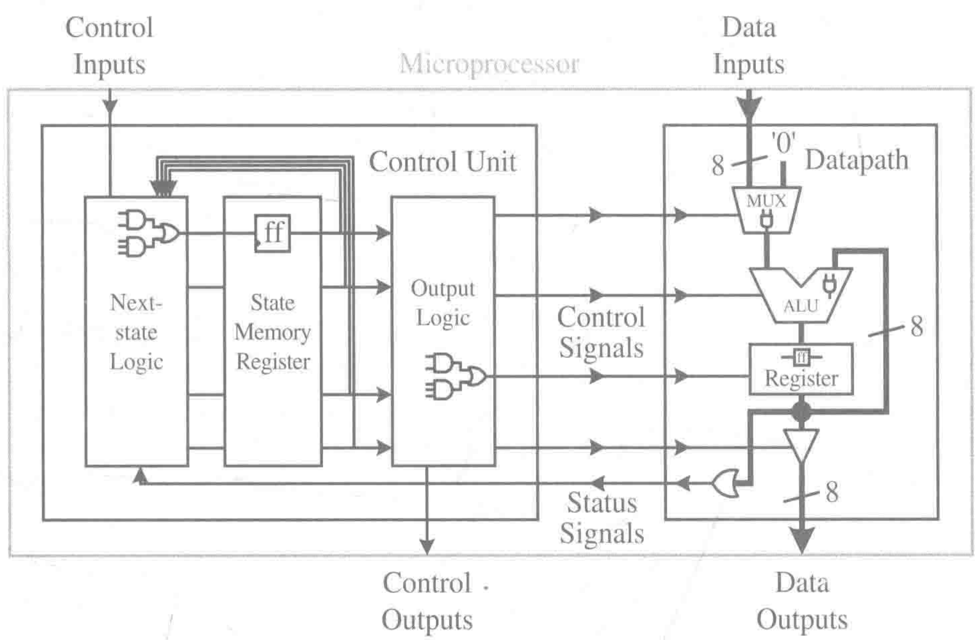
CHAPTER 1

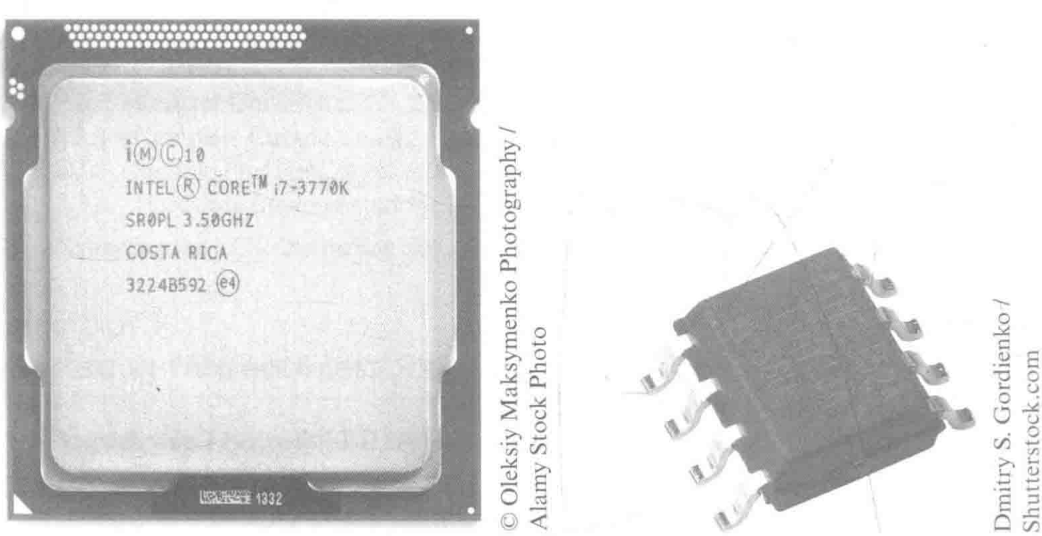
# Introduction to Microprocessor Design



Electronic devices are an integral part of our lives. Every day and everywhere we see and use electronic devices, from cellular telephones to electronic billboards, cars, toys, TVs, elevators, musical greeting cards, personal computers, traffic lights, and many more. Inside each and every one of them, there is a microprocessor that controls their operations. Microprocessors are at the heart of all of these "smart" devices. Their smartness is a direct result of the work of the microprocessor, without which none of these electronic devices would be able to operate as they do.

There are generally two types of microprocessors: **general-purpose microprocessors** and **dedicated microprocessors**. General-purpose microprocessors, such as the Intel Core™ i7 CPU shown in Figure 1.1(a) can perform different tasks under the control of different software programs. General-purpose microprocessors typically are much more powerful in terms of processing power and speed. However, they usually require external components for their memory and supporting input/output (I/O) peripherals. They are used in all personal computers.

Dedicated microprocessors, also known as **microcontrollers** or **application-specific integrated circuits** (ASICs), on the other hand, are designed to perform just one specific task. For example, inside your cell phone is a dedicated microcontroller that does nothing else but control its entire operation. Microcontrollers therefore are usually not as powerful (because they do not need to perform so many tasks) as a microprocessor and are much smaller in size. However, they usually will have the memory and supporting I/O peripherals included inside the chip, hence the entire system can be on a single chip. For example, the Atmel ATtiny13A microcontroller shown in Figure 1.1(b) has built-in flash memory, electrically erasable programmable read-only memory (EEPROM), static random-access memory (SRAM), general-purpose I/Os, timers, serial interface, and analog-to-digital converters (ADC). Dedicated microcontrollers are used in almost all smart electronic devices. Although the small dedicated microcontrollers are not as powerful and are slower in speed as compared to general-purpose microprocessors, they are being sold much more and are used in a lot more places than general-purpose microprocessors.




(a) (b)

**FIGURE 1.1 Microprocessors: (a) General-purpose Intel Core™ i7 CPU; (b) Dedicated Atmel ATtiny13A microcontroller.**