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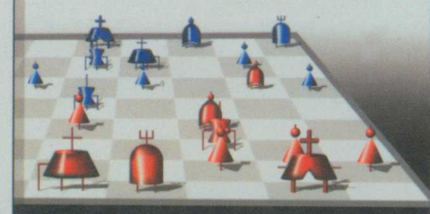
数字逻辑基础与Verilog设计

（英文版）

INTERNATIONAL EDITION

FUNDAMENTALS OF
DIGITAL LOGIC
WITH VERILOG DESIGN

STEPHEN BROWN ZVONKO VRANESIC



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附赠光盘

(加) Stephen Brown
Zvonko Vranesic 著
多 伦 多 大 学

机械工业出版社
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出版者的话

文艺复兴以降，源远流长的科学精神和逐步形成的学术规范，使西方国家在自然科学的各个领域取得了垄断性的优势；也正是这样的传统，使美国在信息技术发展的六十多年间名家辈出、独领风骚。在商业化的进程中，美国的产业界与教育界越来越紧密地结合，计算机学科中的许多泰山北斗同时身处科研和教学的最前线，由此而产生的经典科学著作，不仅擘划了研究的范畴，还揭橥了学术的源变，既遵循学术规范，又自有学者个性，其价值并不会因年月的流逝而减退。

近年，在全球信息化大潮的推动下，我国的计算机产业发展迅猛，对专业人才的需求日益迫切。这对计算机教育界和出版界都既是机遇，也是挑战；而专业教材的建设在教育战略上显得举足轻重。在我国信息技术发展时间较短、从业人员较少的现状下，美国等发达国家在其计算机科学发展的几十年间积淀的经典教材仍有许多值得借鉴之处。因此，引进一批国外优秀计算机教材将对我国计算机教育事业的发展起积极的推动作用，也是与世界接轨、建设真正的世界一流大学的必由之路。

机械工业出版社华章图文信息有限公司较早意识到“出版要为教育服务”。自1998年开始，华章公司就将工作重点放在了遴选、移译国外优秀教材上。经过几年的不懈努力，我们与Prentice Hall，Addison-Wesley，McGraw-Hill，Morgan Kaufmann等世界著名出版公司建立了良好的合作关系，从它们现有的数百种教材中甄选出Tanenbaum，Stroustrup，Kernighan，Jim Gray等大师名家的一批经典作品，以“计算机科学丛书”为总称出版，供读者学习、研究及庋藏。大理石纹理的封面，也正体现了这套丛书的品位和格调。

“计算机科学丛书”的出版工作得到了国内外学者的鼎力襄助，国内的专家不仅提供了中肯的选题指导，还不辞劳苦地担任了翻译和审校的工作；而原书的作者也相当关注其作品在中国的传播，有的还专程为其书的中译本作序。迄今，“计算机科学丛书”已经出版了近百个品种，这些书籍在读者中树立了良好的口碑，并被许多高校采用为正

式教材和参考书籍，为进一步推广与发展打下了坚实的基础。

随着学科建设的初步完善和教材改革的逐渐深化，教育界对国外计算机教材的需求和应用都步入一个新的阶段。为此，华章公司将加大引进教材的力度，在“华章教育”的总规划之下出版三个系列的计算机教材：除“计算机科学丛书”之外，对影印版的教材，则单独开辟出“经典原版书库”；同时，引进全美通行的教学辅导书“Schaum's Outlines”系列组成“全美经典学习指导系列”。为了保证这三套丛书的权威性，同时也为了更好地为学校和老师们服务，华章公司聘请了中国科学院、北京大学、清华大学、国防科技大学、复旦大学、上海交通大学、南京大学、浙江大学、中国科技大学、哈尔滨工业大学、西安交通大学、中国人民大学、北京航空航天大学、北京邮电大学、中山大学、解放军理工大学、郑州大学、湖北工学院、中国国家信息安全测评认证中心等国内重点大学和科研机构在计算机的各个领域的著名学者组成“专家指导委员会”，为我们提供选题意见和出版监督。

这三套丛书是响应教育部提出的使用外版教材的号召，为国内高校的计算机及相关专业的教学度身订造的。其中许多教材均已为M. I. T.，Stanford，U.C. Berkeley，C. M. U. 等世界名牌大学所采用。不仅涵盖了程序设计、数据结构、操作系统、计算机体系结构、数据库、编译原理、软件工程、图形学、通信与网络、离散数学等国内大学计算机专业普遍开设的核心课程，而且各具特色——有的出自语言设计者之手、有的历经三十年而不衰、有的已被全世界的几百所高校采用。在这些圆熟通博的名师大作的指引之下，读者必将在计算机科学的宫殿中由登堂而入室。

权威的作者、经典的教材、一流的译者、严格的审校、精细的编辑，这些因素使我们的图书有了质量的保证，但我们的目标是尽善尽美，而反馈的意见正是我们达到这一终极目标的重要帮助。教材的出版只是我们的后续服务的起点。华章公司欢迎老师和读者对我们的工作提出建议或给予指正，我们的联系方法如下：

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邮政编码：100037

FOREWORD

Chess is a game that provides a splendid vehicle for displaying human intelligence in a competitive environment. During the past 30 years, it has also served as a platform for determining the extent to which machines can emulate intelligent behavior. Many chess programs are available for today's computers. Chess machines, comprising a computer and a chess-playing program, are now capable of defeating even the strongest human players.

The ultimate challenge took place in 1997, when IBM's Deep Blue chess machine defeated the World Champion Garry Kasparov in a six-game match. The essence of this machine are logic circuits, algorithms, and software—coupled with people who know how to use these resources. Although all of these factors are crucial, the greatest leap forward, in terms of chess-playing strength, was made when extremely powerful logic circuits were developed. Most of these circuits are used in general purpose computers, but some are specialized for the chess-playing application. A key reason why the Deep Blue machine is so strong is that it can evaluate about 200 million chess position in one second.

This textbook deals with logic circuits and explains how they are designed. We have included in the book the moves from the decisive sixth game of the 1997 match to remind the reader of the incredible possibilities that are attainable with well-designed logic circuits. Deep Blue played with the white pieces.

Preface

This book is intended for an introductory course in digital logic design, which is a basic course in most electrical and computer engineering programs. A successful designer of digital logic circuits needs a good understanding of basic concepts and a firm grasp of computer-aided design (CAD) tools. The purpose of our book is to provide the desirable balance between teaching the basic concepts and practical application through CAD tools. To facilitate the learning process, the necessary CAD software is included as an integral part of the book package.

A serious drawback of many books on digital logic design is that they cover too much material. A book that covers a large number of topics is not easy to use in a classroom, particularly if the topics are not covered in sufficient depth. Also, in their desire to provide a vast amount of practical advice, the authors often make the text difficult to follow by the students who are still struggling with the fundamental concepts. Our aim is to avoid both of these problems.

The main goals of the book are (1) to teach students the fundamental concepts in classical manual digital design and (2) illustrate clearly the way in which digital circuits are designed today, using CAD tools. Even though modern designers no longer use manual techniques, except in rare circumstances, our motivation for teaching such techniques is to give students an intuitive feeling for how digital circuits operate. Also, the manual techniques provide an illustration of the types of manipulations performed by CAD tools, giving students an appreciation of the benefits provided by design automation. Throughout the book, basic concepts are introduced by way of examples that involve simple circuit designs, which we perform using both manual techniques and modern CAD-tool-based methods. Having established the basic concepts, more complex examples are then provided, using the CAD tools. Thus our emphasis is on modern design methodology to illustrate how digital design is carried out in practice today.

Technology and CAD Support

The book discusses modern digital circuit implementation technologies. We briefly discuss SSI, as well as semi-custom and full-custom technologies. However, the emphasis is on programmable logic devices (PLDs). This is the most appropriate technology for use in a textbook for two reasons. First, PLDs are widely used in practice and are suitable for almost all types of digital circuit designs. In fact, students are more likely to be involved in PLD-based designs at some point in their careers than in any other technology. Second, circuits are implemented in PLDs by end-user programming. Therefore, students can be provided with an opportunity, in a laboratory setting, to implement the book's design examples in actual chips. Students can also simulate the behavior of their designed circuits on their own computers. We use the two most popular types of PLDs for targeting of designs: complex programmable logic devices (CPLDs) and field-programmable gate arrays (FPGAs).

Our CAD support is based on Altera MAX+plusII software. MAX+plusII provides automatic mapping of a design into Altera CPLDs and FPGAs, which are among the most widely used PLDs in the industry. The features of MAX+plusII that are particularly attractive for our purposes are:

- It is a commercial product. The version included with the book supports all major features of the product. Students will be able to easily enter a design into the CAD system, compile the design into a selected device (the choice of device can be changed at any time and the design retargeted to a different device), simulate the functionality and detailed timing of the resulting circuit, and if laboratory facilities are provided at the student's school, implement the designs in actual devices.
- It provides for design entry using both hardware description languages (HDLs) and schematic capture. In the book, we provide examples of design using schematic capture, but we emphasize the HDL-based design because it is the most efficient design method to use in practice. We describe in detail the IEEE Standard Verilog language and use it extensively in examples. The CAD system included with the book has a Verilog compiler, which allows the student to automatically create circuits from the Verilog code and implement these circuits in real chips.
- It can automatically target a design to various types of devices. This feature allows us to illustrate the ways in which the architecture of the target device affects a designer's circuit.
- It can be used on most types of popular computers. We expect that most students will use the version of the software that runs on IBM-compatible computers (running any version of Microsoft windows), which is provided with the book. However, through Altera's university program the software is also available for other machines, such as SUN or HP workstations.

A MAX+plusII CD-ROM is included with each copy of the book. Use of the software is fully integrated into the book so that students can try, firsthand, all design examples. To teach the students how to use this software, the book includes three, progressively advanced, hands-on tutorials.

SCOPE OF THE BOOK

Chapter 1 provides a general introduction to the process of designing digital systems. It discusses the key steps in the design process and explains how CAD tools can be used to automate many of the required tasks.

Chapter 2 introduces the basic aspects of logic circuits. It shows how Boolean algebra is used to represent such circuits. It also gives the reader a first glimpse at Verilog, as an example of a hardware description language that may be used to specify the logic circuits.

The electronic aspects of digital circuits are presented in Chapter 3. This chapter shows how the basic gates are built using transistors and presents various factors that affect circuit performance. The emphasis is on the latest technologies, with particular focus on CMOS technology and programmable logic devices.

Chapter 4 deals with the synthesis of combinational circuits. It covers all aspects of the synthesis process, starting with an initial design and performing the optimization steps needed to generate a desired final circuit. It shows how CAD tools are used for this purpose.

Chapter 5 concentrates on circuits that perform arithmetic operations. It begins with a discussion of how numbers are represented in digital systems and then shows how such numbers can be manipulated using logic circuits. This chapter illustrates how Verilog can be used to specify the desired functionality and how CAD tools provide a mechanism for developing the required circuits. We chose to introduce the number representations at this point, rather than in the very beginning of the book, to make the discussion more meaningful and interesting, because we can immediately provide examples of how numerical information may be processed by actual circuits.

Chapter 6 presents combinational circuits that are used as building blocks. It includes the encoder, decoder, and multiplexer circuits. These circuits are very convenient for illustrating the application of many Verilog constructs, giving the reader an opportunity to discover more advanced features of Verilog.

Storage elements are introduced in Chapter 7. The use of flip-flops to realize regular structures, such as shift registers and counters, is discussed. Verilog-specified designs of these structures are included.

Chapter 8 gives a detailed presentation of synchronous sequential circuits (finite state machines). It explains the behavior of these circuits and develops practical design techniques for both manual and automated design.

Asynchronous sequential circuits are discussed in Chapter 9. While this treatment is not exhaustive, it provides a good indication of the main characteristics of such circuits. Even though the asynchronous circuits are not used extensively in practice, they should be studied because they provide an excellent vehicle for gaining a deeper understanding of the operation of digital circuits in general. They illustrate the consequences of propagation delays and race conditions that may be inherent in the structure of a circuit.

Chapter 10 is a discussion of a number of practical issues that arise in the design of real systems. It highlights problems often encountered in practice and indicates how they can be overcome. Examples of larger circuits illustrate a hierarchical approach in designing digital systems. Complete Verilog code for these circuits is presented.

Chapter 11 introduces the topic of testing. A designer of logic circuits has to be aware of the need to test circuits and should be conversant with at least the most basic aspects of testing.

Appendix A provides a complete summary of Verilog features. Although use of Verilog is integrated throughout the book, this appendix provides a convenient reference that the reader can consult from time to time when writing Verilog code.

Appendices B, C, and D contain a sequence of tutorials on the MAX+plusII CAD tools. This material is suitable for self-study; it shows the student in a step-by-step manner how to use the CAD software provided with the book.

Appendix E gives detailed information about the devices used in illustrative examples. It also includes a brief discussion of TTL technology.

WHAT CAN BE COVERED IN A COURSE

All the material in the book can be covered in 2 one-quarter courses. A good coverage of the most important material can be achieved in a single one-semester, or even a one-quarter, course. This is possible only if the instructor does not spend too much time teaching the intricacies of Verilog and CAD tools. To make this approach possible, we organized the Verilog material in a modular style that is conducive to self-study. Our experience in teaching different classes of students at the University of Toronto shows that the instructor may spend only 2 to 3 lecture hours on Verilog, concentrating mostly on the specification of sequential circuits. The Verilog examples given in the book are largely self-explanatory, and students can understand them easily. Moreover, the instructor need not teach how to use the CAD tools, because the MAX+plusII tutorials in Appendices B, C, and D are suitable for self-study.

The book is also suitable for a course in logic design that does not include exposure to Verilog. However, some knowledge of Verilog, even at a rudimentary level, is beneficial to the students, and it is a great preparation for a job as a design engineer.

One-Semester Course

A natural starting point for formal lectures is Chapter 2. The material in Chapter 1 is a general introduction that serves as a motivation for why logic circuits are important and interesting; students can read and understand this material easily.

The following material should be covered in lectures:

- Chapter 2—all sections.
- Chapter 3—sections 3.1 to 3.7. Also, it is useful to cover sections 3.8 and 3.9 if the students have some basic knowledge of electrical circuits.
- Chapter 4—sections 4.1 to 4.7 and section 4.12.
- Chapter 5—sections 5.1 to 5.5.
- Chapter 6—all sections.
- Chapter 7—all sections.
- Chapter 8—sections 8.1 to 8.9.

If time permits, it would also be very useful to cover sections 9.1 to 9.3 and section 9.6 in Chapter 9, as well as one or two examples in Chapter 10.

One-Quarter Course

In a one-quarter course the following material can be covered:

- Chapter 2—all sections.
- Chapter 3—sections 3.1 to 3.3.
- Chapter 4—sections 4.1 to 4.5 and section 4.12.
- Chapter 5—sections 5.1 to 5.3 and section 5.5.
- Chapter 6—all sections.
- Chapter 7—sections 7.1 to 7.10 and section 7.13.
- Chapter 8—Sections 8.1 to 8.5.

A More Traditional Approach

The material in Chapters 2 and 4 introduces Boolean algebra, combinational logic circuits, and basic minimization techniques. Chapter 2 provides initial exposure to these topics using only AND, OR, NOT, NAND, and NOR gates. Then Chapter 3 discusses the implementation technology details, before proceeding with the synthesis techniques and other types of gates in Chapter 4. The material in Chapter 4 is appreciated better if students understand the technological reasons for the existence of NAND, NOR, and XOR gates, and the various programmable logic devices.

An instructor who favors a more traditional approach may cover Chapters 2 and 4 in succession. To understand the use of NAND, NOR, and XOR gates, it is necessary only that the instructor provide a functional definition of these gates.

VERILOG

Verilog is a complex language, which some instructors feel is too hard for beginning students to grasp. We fully appreciate this issue and have attempted to solve it. It is not necessary to introduce the entire Verilog language. In the book we present the important Verilog constructs that are useful for the design and synthesis of logic circuits. Many other language constructs, such as those that have meaning only when using the language for simulation purposes, are omitted. The Verilog material is introduced gradually, with more advanced features being presented only at points where their use can be demonstrated in the design of relevant circuits.

The book includes more than 140 examples of Verilog code. These examples illustrate how Verilog is used to describe a wide range of logic circuits, from those that contain only a few gates to those that represent digital systems such as a simple processor.

HOMEWORK PROBLEMS

More than 400 homework problems are provided in the book. Solutions to these problems are available to instructors in the *Solutions Manual* that accompanies the book.

LABORATORY

The book can be used for a course that does not include laboratory exercises, in which case students can get useful practical experience by simulating the operation of their designed circuits by using the CAD tools provided with the book. If there is an accompanying laboratory, then a number of design examples in the book are suitable for laboratory experiments. Additional experiments are available on the authors' website.

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Stephen Brown and Zvonko Vranesic

About the Authors

Stephen Brown received his B.A.Sc. degree in Electrical Engineering from the University of New Brunswick, Canada, and the M.A.Sc. and Ph.D. degrees in Electrical Engineering from the University of Toronto. He joined the University of Toronto faculty in 1992, where he is now an Associate Professor in the Department of Electrical & Computer Engineering. He is also Director of Software Development at the Altera Toronto Technology Center.

His research interests include field-programmable VLSI technology and computer architecture. He won the Canadian Natural Sciences and Engineering Research Council's 1992 Doctoral Prize for the best Ph.D. thesis in Canada.

He has won four awards for excellence in teaching electrical engineering, computer engineering, and computer science courses. He is a coauthor of two other books: *Fundamentals of Digital Logic with VHDL Design* and *Field-Programmable Gate Arrays*.

Zvonko Vranesic received his B.A.Sc., M.A.Sc., and Ph.D. degrees, all in Electrical Engineering, from the University of Toronto. From 1963–1965, he worked as a design engineer with the Northern Electric Co. Ltd. in Bramalea, Ontario. In 1968 he joined the University of Toronto, where he is now a Professor in the Departments of Electrical & Computer Engineering and Computer Science. During the 1978–79 academic year, he was a Senior Visitor at the University of Cambridge, England, and during 1984–85 he was at the University of Paris, 6. From 1995 to 2000 he served as Chair of the Division of Engineering Science at the University of Toronto. He is also involved in research and development at the Altera Toronto Technology Center.

His current research interests include computer architecture, field-programmable VLSI technology, and multiple-valued logic systems.

He is a coauthor of four other books: *Computer Organization*, 5th ed.; *Fundamentals of Digital Logic with VHDL Design*; *Microcomputer Structures*; and *Field-Programmable Gate Arrays*. In 1990, he received the Wighton Fellowship for "innovative and distinctive contributions to undergraduate laboratory instruction."

He has represented Canada in numerous chess competitions. He holds the title of International Master.

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