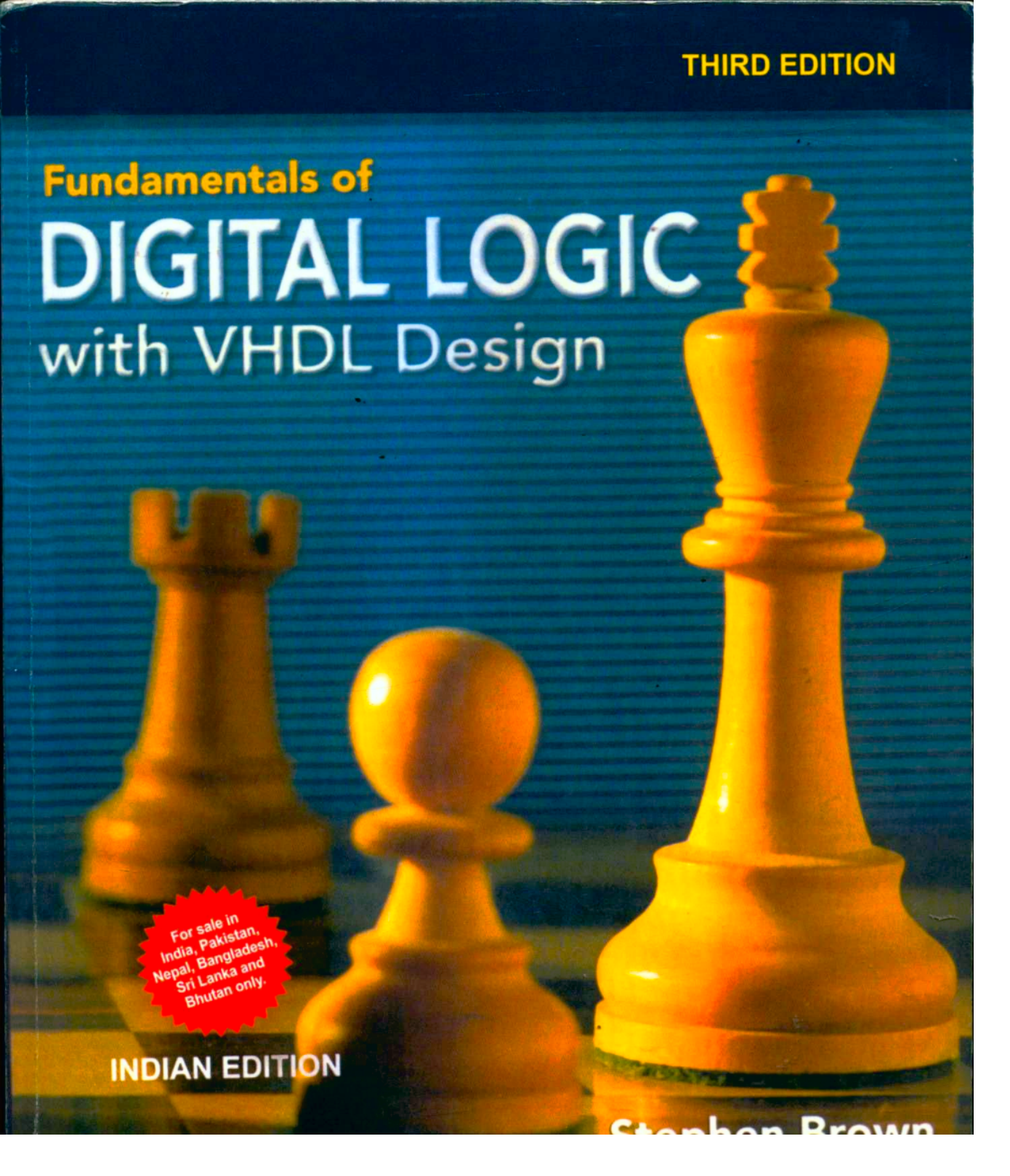
THIRD EDITION

Fundamentals of DIGITAL LOGIC with VHDL Design



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Stephen Brown

FUNDAMENTALS OF DIGITAL LOGIC WITH VHDL DESIGN

THIRD EDITION

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To Susan and Anne

About the Authors

Stephen Brown received the Ph.D. and M.A.Sc. degrees in Electrical Engineering from the University of Toronto, and his B.A.Sc. degree in Electrical Engineering from the University of New Brunswick. He joined the University of Toronto faculty in 1992, where he is now a Professor in the Department of Electrical & Computer Engineering. He also holds the position of Architect at the Altera Toronto Technology Center, a world-leading research and development site for CAD software and FPGA architectures, where he is involved in research activities and is the Director of the Altera University Program.

His research interests include field-programmable VLSI technology, CAD algorithms, 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 is a coauthor of more than 60 scientific research papers and two other textbooks: *Fundamentals of Digital Logic with Verilog Design*, 2nd ed. and *Field-Programmable Gate Arrays*.

He has won multiple awards for excellence in teaching electrical engineering, computer engineering, and computer science courses.

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 Emeritus in the Department of Electrical & Computer Engineering. 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 and field-programmable VLSI technology.

He is a coauthor of four other books: *Computer Organization*, 5th ed.; *Fundamentals of Digital Logic with Verilog Design*, 2nd ed.; *Microcomputer Structures*; and *Field-Programmable Gate Arrays*. In 1990, he received the Wighton Fellowship for "innovative and distinctive contributions to undergraduate laboratory instruction." In 2004, he received the Faculty Teaching Award from the Faculty of Applied Science and Engineering at the University of Toronto.

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

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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.

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. The emphasis is on programmable logic devices (PLDs), which 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 Quartus II software. Quartus II 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 Quartus II 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 emphasize the HDL-based design because it is the most efficient design method to use in practice. We describe in detail the IEEE Standard VHDL language and use it extensively in examples. The CAD system included with the book has a VHDL compiler, which allows the student to automatically create circuits from the VHDL 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. The version of Quartus II provided with the book runs on computers using Microsoft Windows. However, through Altera's university program the software is also available for other machines, such as SUN or HP workstations.

A Quartus II 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. It also introduces the binary numbers.

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 VHDL, 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 VHDL can be used to specify the desired functionality and how CAD tools provide a mechanism for developing the required circuits.