

# **INTRODUCTION TO DIGITAL SYSTEMS**

# **INTRODUCTION TO DIGITAL SYSTEMS**

---

## **Modeling, Synthesis, and Simulation Using VHDL**

**Mohammed Ferdjallah**

*The Virginia Modeling, Analysis and Simulation Center  
Old Dominion University  
Suffolk, Virginia  
and ECPI College of Technology*



**WILEY**

A JOHN WILEY & SONS, INC., PUBLICATION

Copyright © 2011 by John Wiley & Sons, Inc. All rights reserved.

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.

Published simultaneously in Canada.

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Sections 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4470, or on the web at [www.copyright.com](http://www.copyright.com). Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at <http://www.wiley.com/go/permission>.

**Limit of Liability/Disclaimer of Warranty:** While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services or for technical support, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic formats. For more information about Wiley products, visit our web site at [www.wiley.com](http://www.wiley.com).

***Library of Congress Cataloging-in-Publication Data:***

Ferdjallah, Mohammed.

Introduction to digital systems : modeling, synthesis, and simulation using VHDL / Mohammed Ferdjallah.

p. cm.

Includes bibliographical references and index.

ISBN 978-0-470-90055-0 (cloth)

1. Digital electronics. 2. Digital electronics--Computer simulation. 3. VHDL (Computer hardware description language) I. Title.

TK7868.D5F47 2011

621.39'2--dc22

2010041036

Printed in the United States of America

eBooK ISBN: 9781118007716

ePDF ISBN: 9781118007693

ePub ISBN: 9781118007709

10 9 8 7 6 5 4 3 2 1

# CONTENTS

<b>Preface</b>	<b>ix</b>
<b>1 Digital System Modeling and Simulation</b>	<b>1</b>
1.1 Objectives	1
1.2 Modeling, Synthesis, and Simulation Design	1
1.3 History of Digital Systems	2
1.4 Standard Logic Devices	2
1.5 Custom-Designed Logic Devices	3
1.6 Programmable Logic Devices	3
1.7 Simple Programmable Logic Devices	4
1.8 Complex Programmable Logic Devices	5
1.9 Field-Programmable Gate Arrays	6
1.10 Future of Digital Systems	7
Problems	8
<b>2 Number Systems</b>	<b>9</b>
2.1 Objectives	9
2.2 Bases and Number Systems	9
2.3 Number Conversions	11
2.4 Data Organization	13
2.5 Signed and Unsigned Numbers	13
2.6 Binary Arithmetic	16
2.7 Addition of Signed Numbers	17
2.8 Binary-Coded Decimal Representation	19
2.9 BCD Addition	20
Problems	21
<b>3 Boolean Algebra and Logic</b>	<b>24</b>
3.1 Objectives	24
3.2 Boolean Theory	24
3.3 Logic Variables and Logic Functions	25
3.4 Boolean Axioms and Theorems	25
3.5 Basic Logic Gates and Truth Tables	27
3.6 Logic Representations and Circuit Design	27

3.7	Truth Table	28
3.8	Timing Diagram	31
3.9	Logic Design Concepts	31
3.10	Sum-of-Products Design	32
3.11	Product-of-Sums Design	33
3.12	Design Examples	34
3.13	NAND and NOR Equivalent Circuit Design	36
3.14	Standard Logic Integrated Circuits	37
	Problems	39
<b>4</b>	<b>VHDL Design Concepts</b>	<b>46</b>
4.1	Objectives	46
4.2	CAD Tool-Based Logic Design	46
4.3	Hardware Description Languages	47
4.4	VHDL Language	48
4.5	VHDL Programming Structure	48
4.6	Assignment Statements	51
4.7	VHDL Data Types	51
4.8	VHDL Operators	55
4.9	VHDL Signal and Generate Statements	56
4.10	Sequential Statements	58
4.11	Loops and Decision-Making Statements	59
4.12	Subcircuit Design	61
4.13	Packages and Components	61
	Problems	64
<b>5</b>	<b>Integrated Logic</b>	<b>68</b>
5.1	Objectives	68
5.2	Logic Signals	68
5.3	Logic Switches	69
5.4	NMOS and PMOS Logic Gates	70
5.5	CMOS Logic Gates	72
5.6	CMOS Logic Networks	75
5.7	Practical Aspects of Logic Gates	76
5.8	Transmission Gates	79
	Problems	81
<b>6</b>	<b>Logic Function Optimization</b>	<b>87</b>
6.1	Objectives	87
6.2	Logic Function Optimization Process	87
6.3	Karnaugh Maps	87
6.4	Two-Variable Karnaugh Map	89
6.5	Three-Variable Karnaugh Map	90

6.6	Four-Variable Karnaugh Map	91
6.7	Five-Variable Karnaugh Map	93
6.8	XOR and NXOR Karnaugh Maps	94
6.9	Incomplete Logic Functions	94
6.10	Quine–McCluskey Minimization	96
	Problems	99
<b>7</b>	<b>Combinational Logic</b>	<b>105</b>
7.1	Objectives	105
7.2	Combinational Logic Circuits	105
7.3	Multiplexers	106
7.4	Logic Design with Multiplexers	111
7.5	Demultiplexers	112
7.6	Decoders	113
7.7	Encoders	115
7.8	Code Converters	116
7.9	Arithmetic Circuits	120
	Problems	129
<b>8</b>	<b>Sequential Logic</b>	<b>133</b>
8.1	Objectives	133
8.2	Sequential Logic Circuits	133
8.3	Latches	134
8.4	Flip-Flops	138
8.5	Registers	145
8.6	Counters	149
	Problems	158
<b>9</b>	<b>Synchronous Sequential Logic</b>	<b>165</b>
9.1	Objectives	165
9.2	Synchronous Sequential Circuits	165
9.3	Finite-State Machine Design Concepts	167
9.4	Finite-State Machine Synthesis	171
9.5	State Assignment	178
9.6	One-Hot Encoding Method	180
9.7	Finite-State Machine Analysis	182
9.8	Sequential Serial Adder	184
9.9	Sequential Circuit Counters	188
9.10	State Optimization	195
9.11	Asynchronous Sequential Circuits	199
	Problems	201
<b>Index</b>		<b>213</b>

# PREFACE

Digital system design requires rigorous modeling and simulation analysis that eliminates design risks and potential harm to users. Thus, the educational objective of this book is to provide an introduction to digital system design through modeling, synthesis, and simulation computer-aided design (CAD) tools. This book provides an introduction to analytical and computational methods that allow students and users to model, synthesize, and simulate digital principles using very high-speed integrated-circuit hardware description language (VHDL) programming. We present the practical application of modeling and synthesis to digital system design to establish a basis for effective design and provide a systematic tutorial of how basic digital systems function. In doing so, we integrate theoretical principles, discrete mathematical models, computer simulations, and basics methods of analysis. Students and users will learn how to use modeling, synthesis, and simulation concepts and CAD tools to design models for digital systems that will allow them to gain insights into their functions and the mechanisms of their control. Students will learn how to integrate basic models into more complex digital systems. Although the approach designed in this book focuses on undergraduate students, it can also be used for modeling and simulation students who have a limited engineering background with an inclination to digital systems for visualization purposes.

The book includes nine chapters. Each chapter begins with learning objectives that provide a brief overview of the concepts that the reader is about to learn. In addition, the learning objectives can be used as points for classroom discussion. Each chapter ends with problems that will enable students to practice and review the concepts covered in the chapter. Chapter 1 introduces modeling and simulation and its role in digital system evolution. The chapter provides a brief history of modeling and simulation in digital systems, VHDL programming, programmable and reconfigurable systems, and advantages of using modeling and simulation in digital system design. Chapter 2 introduces the mathematical foundations of digital systems and logical reasoning. Described are Boolean theory, its axioms and theorems, and basic logic gates as well as early modeling in digital system design using algebraic manipulations.

Chapter 3 provides an overview of number representations, number conversions, and number codes. The relationships between decimal representation and the less obvious digital number representations are described. Chapter 4 provides a brief history of VHDL programming, the reasons for its creation, and its impact on the evolution of digital systems and modern computer systems. Described are CAD tools, programming structure, and instructions and syntax of VHDL. Chapter 5 provides a simplified view of the progression of integrated systems and their application in

digital logic circuits and computer systems. The role of modeling and simulation in the optimization and verification of digital system design at the transistor level is described. Chapter 6 provides graphical means and Karnaugh maps to streamline and simplify digital system design using visualization schemes. Although these methods are used only when designing circuits with a small number of gates, they provide rudimentary means for the design of automatic CAD tools.

Chapter 7 introduces combinational logic and its applications in multiplexers, decoders, and arithmetic and logic circuits and systems. Chapter 8 introduces sequential logic, with a focus on sequential logic elementary circuits and their applications in complex circuits such as counters and registers. Chapter 9 provides an overview of finite-state machines, especially the synchronous sequential circuit models used to design simple finite-state machines. Also described is asynchronous sequential logic and its advantages and disadvantages for digital systems. All chapters illustrate circuit design using VHDL sample codes that allow students not only to learn and master VHDL programming but also to model and simulate digital circuits.

MOHAMMED FERDJALLAH