# Digital Design

## with RTL Design, VHDL, and Verilog

SECOND EDITION

Frank Vahid

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**FRANK VAHID**
*University of California, Riverside*

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*To my family, Amy, Eric, Kelsi, and Maya;*
*and to all engineers who apply their skills*
*to improve the human condition.*

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# Preface

## TO STUDENTS ABOUT TO STUDY DIGITAL DESIGN

Digital circuits form the basis of general-purpose computers and also of special-purpose devices like cell phones or video game consoles. Digital circuits are dramatically changing the world. Studying digital design not only gives you the confidence that comes with fundamentally understanding how digital circuits work, but also introduces you to an exciting possible career direction. This statement applies regardless of whether your major is electrical engineering, computer engineering, or computer science; in fact, the need for digital designers with strong computer science skills continues to increase. I hope you find digital design to be as interesting, exciting, and useful as I do.

Throughout this book, I have tried not only to introduce concepts in the most intuitive manner, but I have also tried to show how those concepts can be applied to real-world systems, such as pacemakers, ultrasound machines, printers, automobiles, or cell phones.

Young and capable engineering students sometimes leave their major, claiming they want a job that is more "people-oriented." Yet we need those people-oriented students more than ever, as engineering jobs are increasingly people-oriented, in several ways. First, engineers usually work in *tightly integrated groups* involving numerous other engineers, rather than "sitting alone in front of a computer all day" as many students believe. Second, engineers often work *directly with customers*, such as business people, doctors, lawyers, or government officials, and must therefore be able to connect with those customers. Third, and in my opinion most importantly, *engineers build things that dramatically impact people's lives*. Needed are engineers who combine their enthusiasm, creativity, and innovation with their solid engineering skills to invent and build new products that improve people's quality of life.

I have included "Designer Profiles" at the end of most chapters. The designers, whose experience levels vary from just a year to several decades, and whose companies range from small to huge, share with you their experiences, insights, and advice. You will notice how commonly they discuss the people aspects of their jobs. You may also notice their enthusiasm and passion for their jobs.

## TO INSTRUCTORS OF DIGITAL DESIGN

This book has several key features that distinguish it from existing digital design books.

- *RTL design.* In the 1970s/1980s, chips had hundreds or thousands of gates, and hence digital design emphasized gate-level minimization. Today's chips hold millions of gates, and modern design is thus dominated by ***register-transfer level (RTL)*** design. A student exposed to RTL design in a first course will have a more relevant view of the modern digital design field, leading not only to a better appreciation of modern computers and other digital devices, but to a more accurate understanding of careers involving digital design. Such an accurate understanding is critical to attract computing majors to digital design careers, and to create a cadre of engineers with the comfort in both "software" and "hardware" necessary in modern embedded computing system design. Chapter 5 is entirely devoted to RTL design and is one of the only concise introductions to basic RTL design concepts and examples to be found anywhere.

- *Comprehensive and flexible HDL coverage*. HDLs are an important part of modern digital design, but they must be introduced carefully, such that students continue to learn fundamental digital design concepts along with the appropriate role of HDLs. Thus, this book covers HDLs in a separate chapter (Chapter 9), whose subsections each correspond to an earlier chapter, such that Section 9.2 can directly follow Chapter 2, Section 9.3 can follow Chapter 3, Section 9.4 can follow Chapter 4, and Section 9.5 can follow Chapter 5. This approach provides instructors the flexibility to cover HDLs in the latter part of a course only, or intermixed throughout, but in either case clearly showing students that HDLs are a mechanism for supporting digital design while being distinct from basic concepts. Furthermore, rather than the book choosing just one of the popular languages—VHDL, Verilog, or the relatively new SystemC—the book provides equal coverage of all three of those HDLs. We use our extensive experience in synthesis with commercial tools to create HDL descriptions well suited for synthesis, in addition to being suitable for simulation. Furthermore, for courses that cover HDLs in more depth or that have a follow-up course emphasizing more HDL design, two low-cost books have been created (one for VHDL, one for Verilog) specifically to accompany this book. Those HDL-introduction books use the same chapter structure and examples from this textbook, eliminating the common situation of students struggling to correlate their distinct and sometimes contradicting HDL book and digital design book. Our HDL-introduction books discuss language, simulation, and testing concepts in more depth than digital design books that incorporate HDL coverage, providing numerous HDL examples. The HDL books are also usable by themselves for HDL learning or reference. The HDL-introduction books improve upon the plethora of existing HDL books by emphasizing use of the language for real design, clearly distinguishing HDL use for synthesis from HDL use for testing, and by using extensive examples and figures throughout to illustrate concepts. The HDL-introduction books also come with complete PowerPoint slides that use graphics and animations to serve as an easy-to-use tutorial on the HDL.
- *Top-down design versus optimization.* Digital design and logic-size optimization were inseparably intertwined in the 1970s/1980s' small-capacity chip era. This book cleanly distinguishes design concepts from optimization concepts by using a distinct chapter for optimization (Chapter 6), expanding optimization coverage to also include tradeoffs and to include RTL topics. Nevertheless, the book provides an instructor maximum flexibility to introduce optimization at the times and to the extent desired by the instructor. In particular, the optimization chapter's subsections each correspond directly to one earlier chapter, such that Section 6.2 can directly follow Chapter 2, Section 6.3 can follow Chapter 3, Section 6.4 can

follow Chapter 4, and Section 6.5 can follow Chapter 5. The book also emphasizes the modern approach of top-down design, involving capturing desired behavior and then converting to a circuit. At the same time, this book, like other books, uses a concrete bottom-up approach, starting from transistors, and building incrementally up to gates, flip-flops, registers, controllers, datapath components, and RTL.

- *Extensive use of applied examples and figures.* After describing a new concept and providing basic examples, the book provides examples that apply the concept to applications recognizable to a student, like a "seat belt unfastened" warning system, a computerized checkerboard game, a color printer, or a digital video camera. Furthermore, the end of most chapters includes a product profile, intended to give students an even broader view of the applicability of the concepts, and to introduce clever application-specific concepts the students may find interesting—like the idea of beamforming in an ultrasound machine or of filtering in a cellular phone. The book extensively uses figures to illustrate concepts; it contains over 600 figures.
- *Learning through discovery.* The book emphasizes understanding the need for new concepts, which not only helps students learn and remember the concepts, but develops reasoning skills that can apply the concepts to other domains. For example, rather than just defining a carry-lookahead adder, the book shows intuitive but inefficient approaches to building a faster adder, eventually solving the inefficiencies and leading to ("discovering") the carry-lookahead design.
- *Introduction to FPGAs.* The book includes a fully bottom-up introduction to FPGAs, showing students concretely how a circuit can be converted into a bitstream that programs the individual lookup tables, switch matrices, and other programmable components in an FPGA. This concrete introduction eliminates the mystery of the increasingly common FPGA devices.
- *Author-created graphical animated PowerPoint slides.* A rich set of PowerPoint slides is available to instructors. The slides were created by the textbook's author, resulting in consistency of perspective and emphasis between the slides and book. The slides are designed to be a truly effective teaching tool for the instructor. Most slides are graphical, avoiding slides consisting of just bulleted lists of text. The slides make extensive use of animation, where appropriate, to gradually unveil concepts or build up circuits, yet animated slides are carefully created so they can be printed out and understood. Nearly every figure, concept, and example from this book is included in the set of almost 500 slides.
- *Complete solutions manual.* Instructors may obtain a complete solutions manual (about 200 pages) containing solutions to every end-of-chapter exercise in this book. The manual extensively utilizes figures to illustrate solutions.

Many of the above features can be seen in the sample book materials available at http://www.ddvahid.com. Materials are available to instructors via the instructors site .

The second edition of this book includes a rewrite of the RTL design introduction in Chapter 5 to more intuitively introduce the subject, a further emphasis of top-down design (capture and convert) throughout Chapters 2–5, and improvements and additions to the descriptions, examples, and exercises in all chapters of the book.

## HOW TO USE THIS BOOK

This book was designed to allow flexibility for instructors to choose among the most common approaches of material coverage. We describe several approaches below.

### RTL-Focused Approach

An RTL-focused approach would simply cover the first 6 chapters in order:

1. Introduction (Chapter 1)
2. Combinational logic design (Chapter 2)
3. Sequential logic design (Chapter 3)
4. Combinational and sequential component design (Chapter 4)
5. RTL design (Chapter 5)
6. Optimizations and tradeoffs (Chapter 6), to the extent desired
7. Physical implementation (Chapter 7) and/or processor design (Chapter 8), to the extent desired

We think this is a great way to order the material, resulting in students doing interesting RTL designs in about seven weeks. HDLs can be introduced at the end if time permits, or left for a second course on digital design (as done at UCR), or covered immediately after each chapter—all three approaches are common.

### Traditional Approach with Some Reordering

This book can be readily used in a traditional approach that introduces optimization along with basic design, with a slight difference from the traditional approach being the swapping of coverage of combinational components and sequential logic, as follows:

1. Introduction (Chapter 1)
2. Combinational logic design (Chapter 2) followed by combinational logic optimization (Section 6.2)
3. Sequential logic design (Chapter 3) followed by sequential logic optimization (Section 6.3)
4. Combinational and sequential component design (Chapter 4) followed by component tradeoffs (Section 6.4)
5. RTL design (Chapter 5) to the extent desired, followed by RTL optimization/tradeoffs (Section 6.5)
6. Physical implementation (Chapter 7) and/or processor design (Chapter 8), to the extent desired

This is a reasonable and effective approach, completing all discussion of one topic (e.g., FSM design as well as optimization) before moving on to the next topic. The reordering from a traditional approach introduces basic sequential design (FSMs and controllers) before combinational components (e.g., adders, comparators, etc.). Such reordering may lead into RTL design more naturally than a traditional approach, following instead an approach of increasing abstraction rather than the traditional approach that separates combinational and sequential design. HDLs can again be introduced at the end, left for another course, or integrated after each chapter. This approach could also be used as an intermediary step when migrating from a traditional approach to an RTL approach. Migrating might involve gradually postponing the Chapter 6 sections—for example, covering Chapters 2 and 3, and then Sections 6.2 and 6.3, before moving on to Chapter 4.

### Traditional Approach

This book could also be used in a traditional approach, as follows:

1. Introduction (Chapter 1)
2. Combinational logic design (Chapter 2) followed by combinational logic optimization (Section 6.2)
3. Combinational component design (Sections 4.1, 4.3–4.8) followed by combinational component tradeoffs (Section 6.4—Faster Adders)
4. Sequential logic design (Chapter 3) followed by sequential logic optimization (Section 6.3)
5. Sequential component design (Sections 4.9, 4.10) followed by sequential component tradeoffs (Section 6.4—Smaller Multiplier)
6. RTL design (Chapter 5) to the extent desired, followed by RTL optimization/tradeoffs (Section 6.5)
7. Physical implementation (Chapter 7) and/or processor design (Chapter 8), to the extent desired.

Coverage of the first five topics has been the most widespread approach during the past two decades, with the above adding RTL design towards the end of the approach. Although the emphasized distinction between combinational and sequential design may no longer be relevant in the era of RTL design (where both types of design are intermixed), some people believe that such distinction makes for an easier learning path. HDLs can be included at the end, left for a later course, or integrated throughout.

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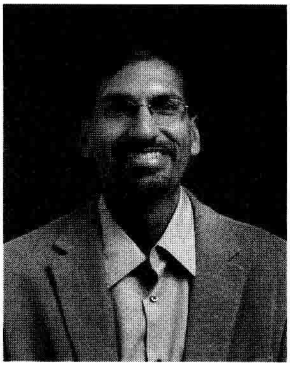
## ABOUT THE COVER

The cover's image of shrinking chips is more than just a nice visual; the image graphically depicts the amazing real-life phenomenon of digital circuits ("computer chips") shrinking in size by about one half every 18 months, for several decades now, a phenomenon referred to as Moore's Law. Such shrinking has enabled incredibly powerful computing circuits to fit inside tiny devices, like modern cell phones, medical devices, and portable video games.

## ABOUT THE AUTHOR



Frank Vahid is a Professor of Computer Science and Engineering at the University of California, Riverside. He received his bachelor's degree in electrical engineering from the University of Illinois at Urbana-Champaign, and his master's and doctoral degrees in computer science from the University of California, Irvine. He has worked for Hewlett Packard and AMCC, and has consulted for Motorola, NEC, Atmel, Cardinal Health, and several other engineering firms. He is the inventor on three U.S. patents, has published over 150 research papers and two books on embedded systems, and helped establish the Embedded Systems Week conference. He established UCR's Computer Engineering program, and has received several UCR teaching awards. His research includes incorporating FPGAs into embedded systems, and networked sensor blocks that ordinary people can configure to monitor their surroundings.

See this book's website at http://www.ddvahid.com for additional book materials, for access to the publisher's book website and instructor materials, or to submit comments, corrections, or suggestions.

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CHAPTER 1

# Introduction

## 1.1 DIGITAL SYSTEMS IN THE WORLD AROUND US

Meet Arianna. Arianna is a five-year-old girl who lives in California. She's a cheerful, outgoing kid who loves to read, play soccer, dance, and tell jokes that she makes up herself.

One day, Arianna's family was driving home from a soccer game. She was in the middle of excitedly talking about the game when suddenly the van in which she was riding was clipped by a car that had crossed over to the wrong side of the highway. Although the accident wasn't particularly bad, the impact caused a loose item from the rear of the van to project forward inside the van, striking Arianna in the back of the head. She became unconscious.

Arianna was rushed to a hospital. Doctors immediately noticed that her breathing was very weak—a common situation after a severe blow to the head—so they put her onto a ventilator, which is a medical device that assists with breathing. She had sustained brain trauma during the blow to the head, and she remained unconscious for several weeks. All her vital signs were stable, except she continued to require breathing assistance from the ventilator. Patients in such a situation sometimes recover, and sometimes they don't. When they do recover, sometimes that recovery takes many months.