THE ART OF DIGITAL DESIGN

An Introduction To Top-Down Design

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FRANKLIN PROSSER

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Preface

This is an introduction to the art of digital hardware design. The design of computer hardware, once the exclusive province of the electrical engineer, is now of vital interest to the computer scientist, whereas techniques for the systematic solution of problems—the computer scientist's specialty —are of increasing importance to the electrical engineer.

Traditional approaches to design, which evolved prior to the integrated circuit, place great emphasis on the hardware devices themselves. In earlier times, this was natural, since the devices were so expensive that hardware costs controlled design. This led to the development of many complex methods of logic minimization, state assignment, handling asynchronous circuits, and so on, that are now little used due to the low cost and great power and flexibility of modern digital components. The complexity of traditional design methods actually can interfere with the designer's ability to create a straightforward, understandable, and correct design!

When we first studied digital design, we consulted traditional textbooks and practiced traditional design methods, but we found that these methods did not really give us much help in solving complex digital hardware problems. A vast body of vital design knowledge was missing from the books, and there was a great lack of systematic methodology for dealing with a digital problem as a system. Eventually, we realized that

the traditional emphasis was misplaced. The difficult part of digital design is not choosing or assembling the hardware devices, but rather is understanding the problem and developing a systematic solution for the system architecture and its control. For this book, we have looked closely at each design technique, and have been ruthless in eliminating methods that do not contribute substantially to the goal of clear and correct design.

Here is our thesis: We must approach hardware design problems from the top, remaining aloof from hardware commitments as long as we can. We must thoroughly understand the problem and must let the problem requirements guide us to suitable hardware, rather than allow premature hardware selections to force us into unsuitable design decisions.

With the realization that the human cost of designing and maintaining a digital system far exceeds the cost of the materials, digital designers are developing a new philosophy toward the design process. This new design approach, which this book exploits, insists that our design tools must materially assist the designer to understand, solve, and document complex hardware and software problems—if necessary, at the cost of additional hardware. The designer's mind must be uncluttered by unnecessary detail. To one experienced in modern computer programming, this has a familiar sound. Software design methodology has undergone drastic improvements in recent years. The software world accepts as valid and powerful such concepts as structured programming and top-down design. This book is a contribution in the same spirit to the field of digital hardware design.

COURSE LEVEL

This book is for self-study and for classroom use. It should benefit the student or professional unsophisticated in digital hardware, yet it provides an opportunity for old hands to come to grips with some modern trends in basic design. For background, we assume that the reader has an elementary knowledge of computer problem solving in a high-level language and has an elementary exposure to the structure of computers and the use of assembly language. The student should be familiar with number systems such as binary, octal, and hexadecimal, and with number representations, particularly two's complement. We assume no prior knowledge of electronics or hardware other than Ohm's Law and simple formulas for series and parallel resistances.

In a college curriculum, this book is suitable for a first course in digital design. The course may be at the middle or upper undergraduate level in computer science or electrical engineering. The text is close to the spirit of the ACM Curriculum 78 course CS4 (Introduction to Computer Organization),† and covers over 85 percent of the material suggested

†*Communications of the ACM 22*, No. 3 (March 1979), pages 147-165.

therein. For electrical engineers, this text is a modernization of the traditional first course in digital design. The text emphasizes the solution of design problems rather than the study of hardware. It uses modern philosophies advocated in the IEEE proposed courses DL-1 and DL-2.†

In sum, the computer science student should feel at home with the structured approach and will be delighted to find that he or she can successfully design and understand complex hardware. The electrical engineering student will gain insight into modern, systematic design style and will develop an understanding of the computer scientist's emphasis on structure.

PLAN OF THE BOOK

This book first provides a thorough foundation for design, emphasizing basic hardwired design. It then introduces microprogramming and microprocessor-based design and prepares the student for further study of these topics. Throughout, we apply the principles of top-down design.

The book has four parts. Three of the parts form a sequence leading systematically from logic fundamentals through digital design with microcomputers, with emphasis on solving digital problems using hardwired structures of the complexity of medium- and large-scale integration (MSI and LSI). The ordering of the topics is from primitive to complex, the natural way. The fourth part is a collection of information on digital technology that the student may read whenever appropriate. Part IV does not depend on the previous parts of the book.

Part I develops the tools for digital design. In these four chapters, we present the theory and formalism required for systematic digital design. Chapter 1 covers the theory of logical expressions—Boolean algebra, truth tables, and useful simplification techniques. Chapter 2 presents the conversion between logic expressions and hardware diagrams, using elementary small-scale integration circuits. This chapter introduces the crucial distinction between voltage and logic, and develops the mixed-logic method for drafting physical circuits from logic expressions. Chapter 3 develops a collection of basic design tools: useful combinational building blocks such as the multiplexer, decoder, and arithmetic logic unit. The treatment emphasizes the systematic uses of the building blocks. Chapter 4 introduces the theory of circuits with memory—the sequential circuits. After establishing the necessary theory and use of basic sequential elements such as flip-flops, we describe standard sequential building blocks such as storage registers, shift registers, random access memories, and read only memories.

Part II explores the art of digital design at the hardwired MSI and LSI level. The theme of these five chapters is that a designer must understand

†*IEEE Computer 10*, No. 12, December 1977, pages 76–79.

the problem before becoming committed to chips and wires—top-down design. Chapter 5 introduces the structure of a digital hardware problem solution—the architecture and the control. We present a hardware flowchart method for expressing control algorithms that allows clear, systematic synthesis of state generators and output signals. Chapter 6 is a series of digital design examples that form a framework for showing systematic solutions of common design situations at the MSI level. In Ch. 7, we execute a large-scale design—a complete minicomputer—using top-down style. Chapter 8 translates the minicomputer design into hardware, using the principle of deferring the hardware decisions. Chapter 9 introduces a limited asynchronous design technique by implementing a Teletype interface to the minicomputer.

Part III bridges the gap between hardware and software. Here we consider the uses of modern LSI technology—microprogramming, bit slices, microprocessors. Chapter 10 discusses microprogramming and its widespread impact on computer design. As an illustration, we show how to convert the minicomputer of Part II into a microprogrammed version. Chapter 11 is an introduction to the use of conventional microprocessors and microcomputers in digital design. Part III is intended to serve as a broad introduction rather than an in-depth treatment of these topics.

In its single chapter, Part IV contains material on digital technology. The topics in Ch. 12 are independent of previous material; the student may explore the treatment whenever he needs specific hardware information. Representative topics are power systems and power distribution, reading integrated circuit data sheets, handling pull-up resistors, clocks, noise problems, and line driving.

SUGGESTIONS FOR COURSE CONTENT

This book provides abundant material for a semester or two-quarter course at the undergraduate level, and adequate material for a year's study. For more compressed schedules, here are some guidelines for selecting course topics. First, Ch. 12 (Part IV) provides a "buffer" in that the instructor can adjust the degree of coverage of hardware technology without disturbing the main text.

We assume that students who pursue the study of digital design will take subsequent courses that deal in depth with microprogramming and microprocessor-based design. In such event, a compressed schedule using this book might cover Parts I and II, and, if time permits, Ch. 10.

Where the instructor wishes to include all of Part III, a shortened sequence might also use Chs. 1-5; several of the design examples in Ch. 6; Chs. 7 and 8, excluding the treatment of the "operate" microinstruction; and, time permitting, Ch. 9. The remarks at the beginning of Ch. 6 will help in determining which design examples to include.

Laboratory experience is a vital part of any study of digital design. In our courses, taught for several years at the University of Wyoming and Indiana University, the students construct and study the complete minicomputer of Chs. 7, 8, and 9. We believe that lengthy experiments on individual gates, flip-flops, and registers are unnecessary; the laboratory time is better spent working with the design and implementation of more complex systems. Students will master individual components in a natural way while studying the structure of larger systems. In any event, we encourage instructors to provide a digital laboratory to accompany the course, for, after all, no design works until it is built!

We gratefully acknowledge the valuable contributions of our colleague, Daniel Friedman, who served enthusiastically as "reviewer without portfolio."

An Instructor's Manual is available for this book, giving suggestions for teaching the course and laboratory, and providing answers to the end-of-chapter exercises.

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Part IV

DIGITAL TECHNOLOGY

part I

Tools for Digital Design

chapter 1

Describing Logic Equations

Before you begin this journey into digital design, it is important that you understand the philosophy that will guide your study. If you have not read the preface, do so now before you go on. The preface discusses the issues that give rise to the need for good style and structure in digital design. Also, the preface contains an outline of the book, which will give you a perspective on where you are heading and how you will get there. It is particularly important that you understand this book's approach to the details of digital hardware. The overriding emphasis is to let the problem solution dictate the hardware, rather than allowing premature hardware commitments to coerce the solution. This conscious suppression of hardware detail during most of the design pays big dividends. Chips and wires and power supplies are still important—they are vital to success, and you will need a good background in many areas of digital technology in order to become an accomplished designer—but too often in digital design the hardware has dominated the solution to the problem. To head off this common malady, we have placed in Part IV of this book almost all the technology needed for your introduction to digital design. This information does not depend on the material in Parts I through III. Read the topics in Part IV as you require or desire them while you are progressing through the first three parts of the text.