Second Edition

COMPUTER ORGANIZATION

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To Liz, Anne, and Shirley

PREFACE

This book is intended for use in a first-level course on "computer organization" in computer science and electrical engineering curricula. The book is self-contained, assuming only that the reader has a basic knowledge of computer programming in a high-level language. Many students who study computer organization will have had an introductory course on digital logic circuits. Therefore, this subject is not covered in the main body of the book. However, we have provided an extensive appendix on logic circuits for those students who need it.

Our resolve to write a book stems from our experience in teaching computer organization to three distinct types of undergraduates: computer science specialists, electrical engineering undergraduates, and engineering science undergraduates. We have always approached the teaching of courses in this area from as practical a point of view as possible. Thus, a major choice in shaping the contents of the book was to illustrate the principles of computer organization by using a number of extensive examples drawn from commercially available computers.

Second, we feel that it is important to recognize that digital system design is not a straightforward process of applying "optimal design" algorithms. Many design decisions are based largely on heuristic judgment and tend to be a compromise between extreme alternatives. Thus it is our goal to convey these notions to the reader.

Third, we have endeavoured to provide sufficient details to force the student to dig beyond the surface when dealing with ideas that seem to be intuitively obvious. We believe that this is best accomplished by giving real examples that are adequately documented. Block diagrams are a powerful means of describing organizational features of a computer. However, they can easily lead to an oversimplified view of the problems involved. Hence, they must be accompanied by the details of implementation alternatives.

We use a number of real machines for illustrative purposes. Our main examples are drawn from the following computers: PDP-11, VAX-11, IBM 370, HP3000, M6800, M6809, M68000, and Intel 8085. The PDP-11 is used for examples in many parts of the book. Its manageable size and complexity make it suitable for teaching purposes. Moreover, it has had considerable influence on instruction set and addressing mode design in small computers.

The book is aimed at a one-semester course in computer science or electrical engineering programs. It is suitable for both hardware- and software-oriented students. There is a greater emphasis on hardware since we feel that this is the way computer organization should be taught. It is a mistake to describe computer structures solely through the eyes of a programmer, particularly for people who work with systems that involve a variety of equipment, interfacing, and communication facilities. However, although the emphasis is on computer hardware, we have addressed a number of software issues and discussed representative instances of software-hardware trade-offs in the implementation of various components of a computing system.

Let us review the topics covered in sequence, chapter by chapter. The first eight chapters cover the basic principles of computer organization. The remaining four chapters deal with peripheral devices, system software, microprocessors, and computer communications.

Chapter 1 provides an overview of computer structure and informally introduces a number of terms that are dealt with in more depth in the remainder of the book. A discussion is included of the basic ways that the standard functional units can be interconnected to form a complete computing system.

Chapter 2 gives a methodical treatment of addressing techniques and instruction sequencing. The PDP-11 minicomputer is used to illustrate the basic concepts. Numerous programs and program segments at the machine instruction level are used to discuss loops, subroutines, and simple input-output programming.

Chapter 3 continues the discussion of instruction sets that was begun in Chapter 2 and focuses on some of the problems encountered because of the "bit-space" limitations of short word-length machines. Instruction sets in the VAX-11, the IBM 370, and the HP3000 are introduced. They illustrate the possibilities afforded by longer word lengths and stack-oriented design. The influence of high-level language programming on the design of these machines is discussed.

Chapter 4 begins with a register-transfer-level treatment of the implementation of instruction fetching and execution in a processor. The constraints imposed by various busing arrangements are explained, followed by a discussion of both hardwired and microprogrammed control.

Chapter 5 extends the discussion of microprogrammed control. The alternatives of fully decoded command words and partially encoded command words are treated, followed by a rather detailed analysis of the "next-address" generation problem in microprogram sequencing. The use of bit slices in designing microprogrammed machines is discussed.

Input-output organization is developed in Chapter 6. The basics of I/O data transfer synchronization are presented, and then a series of increasingly complex I/O structures is explained. Direct-memory access methods and interrupts are introduced, and then these ideas are extended to a discussion of channels. Three popular bus standards, multibus, S-100, and IEEE-488, are also presented.

Chapter 7 treats the arithmetic unit of a computer. It begins with a discussion of fixed-point add, subtract, multiply, and divide hardware, operating on 2's-complement numbers. Lookahead adders and high-speed array multipliers are included. Floating-point number representations and operations, including the IEEE standard, are presented.

Semiconductor memories are discussed in Chapter 8. Multiple-module memory systems and caches are explained as ways of increasing main memory bandwidth. Various cache mapping methods are presented and virtual-memory systems are discussed in some detail.

A variety of peripheral devices are dealt with in Chapter 9. Cathode-ray tube terminals and graphics displays are analyzed in detail. This is followed by a discussion of magnetic disks, drums, and tapes.

Chapter 10 gives an introduction to the subject of operating-system software, including linkers, loaders, and scheduling techniques.

An extensive treatment of microprocessors is provided in Chapter 11. Complete instruction sets, together with some comparative analyses, are given for Motorola's 6800, 6809, and 68000 and for Intel's 8085. Input-output aspects of microcomputer systems are emphasized.

Chapter 12 is an introduction to a number of topics in computer communications. Synchronous and asynchronous protocols for data transmission are considered. This is followed by a brief description of local area and wide area networks.

Most of the material in this book can be covered in a 12-to-15 week course, with 3 lecture hours per week. However, as well as being suited for the usual undergraduate class teaching environment, we feel that the material is appropriate for self-study by graduates who have not specialized in computers but who have taken introductory courses or have work experience in the area. The use of real (commercially available) computers in our examples makes the book attractive to the latter readership.

This second edition of the book contains substantial additions that update and extend the material of the first edition. The additional material includes the following:

- VAX-11 instruction set and addressing modes in Chapter 3
- Discussion of bit slices in Chapter 5
- Bus standards in Chapter 6
- IEEE floating-point standard in Chapter 7
- Dynamic memories and the VAX-11 virtual-memory system in Chapter 8
- M6809 and M68000 microprocessors in Chapter 11 and Appendix C
- Local area networks in Chapter 12

We should note that all of the material on I/O and buses has been consolidated in Chapter 6. A number of sections have also been extensively rewritten in order to update the material to be consistent with technology changes in the past few years.

The authors wish to express their thanks to all the people who have helped during the preparation of this second edition. We are especially grateful for the detailed, constructive criticism of the complete manuscript by Professors Harold Stone and Alfred Weaver. Professors Mary Jane Irwin and Henry Chuang provided useful suggestions in the planning stages for the second edition. Professor Tom Hull gave helpful advice on the floating-point section in Chapter 7. We also wish to acknowledge the typing work of Cathy Cheung.

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CONTENTS

CHAPTER
ONE
BASIC STRUCTURE OF COMPUTERS

The objective of this chapter is to introduce some basic concepts and associated terminology. We will give only a broad overview of the fundamental characteristics of computers, leaving the more detailed and precise discussion to the subsequent chapters.

Let us first define the meaning of the word "digital computer" or simply "computer," which is often misunderstood, despite the fact that most people take it for granted. In its simplest form, a contemporary *computer* is a fast electronic calculating machine, which accepts digitized "input" information, processes it according to a "program" stored in its "memory," and produces the resultant "output" information.

1.1 FUNCTIONAL UNITS

The word computer encompasses a large variety of machines, widely differing in size, speed, and cost. It is fashionable to use more specific words to represent some subclasses of computers. Smaller machines are usually called *minicomputers*, which is a reflection on their relatively lower cost, size, and computing power. In the early 1970s the term *microcomputer* was coined to describe a very small computer, low in price, and consisting of only a few very large-scale integrated (VLSI) circuit packages.

Large computers, sometimes called *mainframes*, are quite different from minicomputers and microcomputers in size, processing power, cost, and the complexity and sophistication of their design. Yet the basic concepts are essentially the same for all classes of computers, relying on a few well-defined ideas which we will attempt to explain.

In its simplest form, a computer consists of five functionally independent main parts: input, memory, arithmetic and logic, output, and control units, as