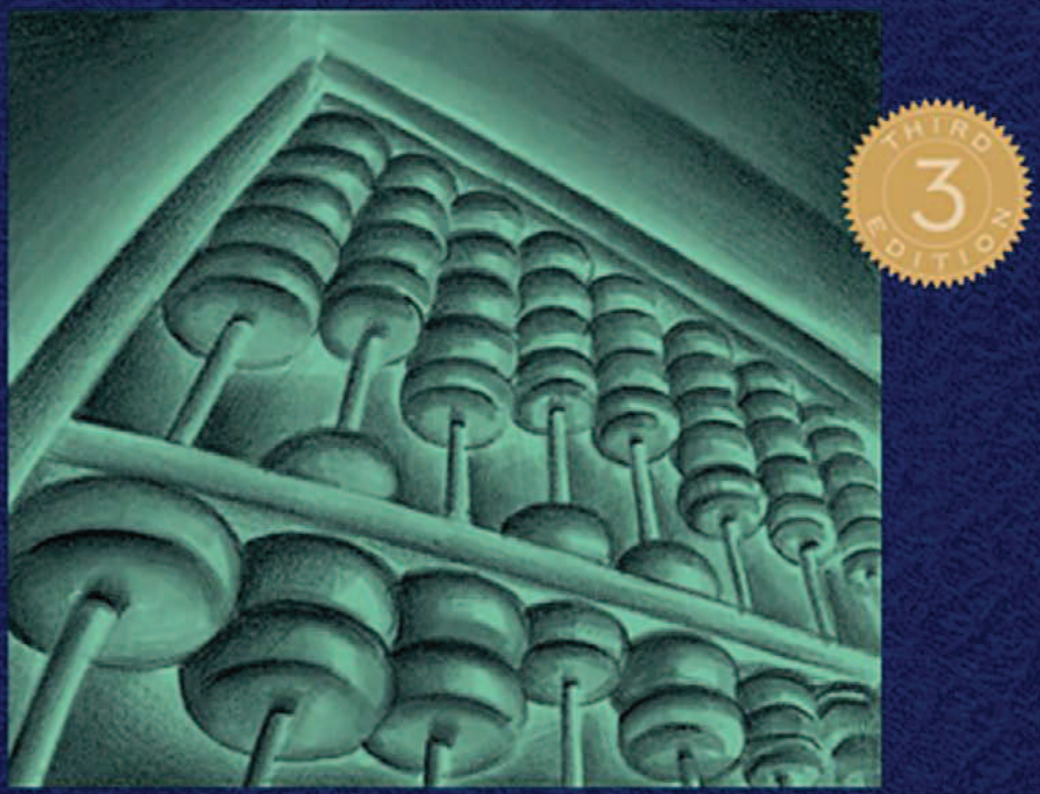
COMPUTER ORGANIZATION AND DESIGN

THE HARDWARE/SOFTWARE INTERFACE



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THIRD EDITION

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Computer Organization and Design

THE HARDWARE/SOFTWARE INTERFACE

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Preface

The most beautiful thing we can experience is the mysterious.
It is the source of all true art and science.

Albert Einstein, *What I Believe*, 1930

About This Book

We believe that learning in computer science and engineering should reflect the current state of the field, as well as introduce the principles that are shaping computing. We also feel that readers in every specialty of computing need to appreciate the organizational paradigms that determine the capabilities, performance, and, ultimately, the success of computer systems.

Modern computer technology requires professionals of every computing specialty to understand both hardware and software. The interaction between hardware and software at a variety of levels also offers a framework for understanding the fundamentals of computing. Whether your primary interest is hardware or software, computer science or electrical engineering, the central ideas in computer organization and design are the same. Thus, our emphasis in this book is to show the relationship between hardware and software and to focus on the concepts that are the basis for current computers.

The audience for this book includes those with little experience in assembly language or logic design who need to understand basic computer organization as well as readers with backgrounds in assembly language and/or logic design who want to learn how to design a computer or understand how a system works and why it performs as it does.

About the Other Book

Some readers may be familiar with *Computer Architecture: A Quantitative Approach*, popularly known as Hennessy and Patterson. (This book in turn is called Patterson and Hennessy.) Our motivation in writing that book was to describe the principles of computer architecture using solid engineering funda-

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then quantitative cost/performance trade-offs. We used an approach that combined examples and measurements, based on commercial systems, to create realistic design experiences. Our goal was to demonstrate that computer architecture could be learned using quantitative methodologies instead of a descriptive approach. It is intended for the serious computing professional who wants a detailed understanding of computers.

A majority of the readers for this book do not plan to become computer architects. The performance of future software systems will be dramatically affected, however, by how well software designers understand the basic hardware techniques at work in a system. Thus, compiler writers, operating system designers, database programmers, and most other software engineers need a firm grounding in the principles presented in this book. Similarly, hardware designers must understand clearly the effects of their work on software applications.

Thus, we knew that this book had to be much more than a subset of the material in *Computer Architecture*, and the material was extensively revised to match the different audience. We were so happy with the result that the subsequent editions of *Computer Architecture* were revised to remove most of the introductory material; hence, there is much less overlap today than with the first editions of both books.

Changes for the Third Edition

We had six major goals for the third edition of *Computer Organization and Design:* make the book work equally well for readers with a software focus or with a hardware focus; improve pedagogy in general; enhance understanding of program performance; update the technical content to reflect changes in the industry since the publication of the second edition in 1998; tie the ideas from the book more closely to the real world *outside* the computing industry; and reduce the size of this book.

First, the table on the next page shows the hardware and software paths through the material. Chapters 1, 4, and 7 are found on both paths, no matter what the experience or the focus. Chapters 2 and 3 are likely to be review material for the hardware-oriented, but are essential reading for the software-oriented, especially for those readers interested in learning more about compilers and object-oriented programming languages. The first sections of Chapters 5 and 6 give overviews for those with a software focus. Those with a hardware focus, however, will find that these chapters present core material; they may also, depending on background, want to read Appendix B on logic design first and the sections on microprogramming and how to use hardware description languages to specify control. Chapter 8 on input/output is key to readers with a software focus and should be read if time permits by others. The last chapter on multiprocessors and clusters is again a question of time for the reader. Even the history sections show this balanced focus; they include short histories of programming languages, compilers, numerical software, operating systems, networking protocols, and databases.

Chapter or Appendix	*Sections*	*Software Focus*	*Hardware Focus*
1. Computer Abstractions and Technology	1.1 to 1.6		
	1.7 (History)		
2. Instructions: Language of the Computer	2.1 to 2.11		
	2.12 (Compilers)		
	2.13 (C sort)		
	2.14 (Java)		
	2.15 to 2.18		
	2.19 (History)		
3. Arithmetic for Computers	3.1 to 3.11		
	3.12 (History)		
D. RISC instruction set architectures	D.1 to D.19		
4. Assessing and Understanding Performance	4.1 to 4.6		
	4.7 (History)		
B. The Basics of Logic Design	B.1 to B.13		
5. The Processor: Datapath and Control	5.1 (Overview)		
	5.2 to 5.7		
	5.8 (Microcode)		
	5.9 (Verilog)		
	5.10 to 5.12		
	5.13 (History)		
C. Mapping Control to Hardware	C.1 to C.6		
6. Enhancing Performance with Pipelining	6.1 (Overview)		
	6.2 to 6.6		
	6.7 (verilog)		
	6.8 to 6.9		
	6.10 to 6.12		
	6.13 (History)		
7. Large and Fast: Exploiting Memory Hierarchy	7.1 to 7.8		
	7.9 (History)		
8. *Storage, Networks, and Other Peripherals*	8.1 to 8.2		
	8.3 (Networks)		
	8.4 to 8.10		
	8.13 (History)		
9. Multiprocessors and Clusters	9.1 to 9.10		
	9.11 (History)		
A. Assemblers, Linkers, and the SPIM Simulator	A.1 to A.12		
Computers in the Real World	Between Chapters		

Read carefully Read if have time Reference

Review or read Read for culture

The next goal was to improve the exposition of the ideas in the book, based on difficulties mentioned by readers of the second edition. We added five new book elements to help. To make the book work better as a reference, we placed definitions of new terms in the margins at their first occurrence. We hope this will help readers find the sections when they want to refer back to material they have already read. Another change was the insertion of the "Check Yourself" sections, which we added to help readers to check their comprehension of the material on the first time through it. A third change is that added extra exercises in the "For More Practice" section. Fourth, we added the answers to the "Check Yourself" sections and to the For More Practice exercises to help readers see for themselves if they understand the material by comparing their answers to the book. The final new book element was inspired by the "Green Card" of the IBM System/360. We believe that you will find that the MIPS Reference Data Card will be a handy reference when writing MIPS assembly language programs. Our idea is that you will remove the card from the front of the book, fold it in half, and keep it in your pocket, just as IBM S/360 programmers did in the 1960s.

Third, computers are so complex today that understanding the performance of a program involves understanding a good deal about the underlying principles and the organization of a given computer. Our goal is that readers of this book should be able to understand the performance of their progams and how to improve it. To aid in that goal, we added a new book element called "Understanding Program Performance" in several chapters. These sections often give concrete examples of how ideas in the chapter affect performance of real programs.

Fourth, in the interval since the second edition of this book, Moore's law has marched onward so that we now have processors with 200 million transistors, DRAM chips with a billion transistors, and clock rates of multiple gigahertz. The "Real Stuff" examples have been updated to describe such chips. This edition also includes AMD64/IA-32e, the 64-bit address version of the long-lived 80x86 architecture, which appears to be the nemesis of the more recent IA-64. It also reflects the transition from parallel buses to serial networks and switches. Later chapters describe Google, which was born after the second edition, in terms of its cluster technology and in novel uses of search.

Fifth, although many computer science and engineering students enjoy information technology for technology's sake, some have more altruistic interests. This latter group tends to have more women and underrepresented minorities. Consequently, we have added a new book element, "Computers in the Real World," two-page layouts found between each chapter. Our perspective is that information technology is more valuable for humanity than most other topics you could study—whether it is preserving our art heritage, helping the Third World, saving our environment, or even changing political systems—and so we demonstrate our view with concrete examples of nontraditional applications. We think readers of these segments will have a greater appreciation of the computing culture beyond

the inherently interesting technology, much like those who read the history sections at the end of each chapter

Finally, books are like people: they usually get larger as they get older. By using technology, we have managed to do all the above and yet shrink the page count by hundreds of pages. As the table illustrates, the core portion of the book for hardware and software readers is on paper, but sections that some readers would value more than others are found on the companion CD. This technology also allows your authors to provide longer histories and more extensive exercises without concerns about lengthening the book. Once we added the CD to the book, we could then include a great deal of free software and tutorials that many instructors have told us they would like to use in their courses. This hybrid paper-CD publication weighs about 30% less than it did six years ago—an impressive goal for books as well as for people.

Instructor Support

We have collected a great deal of material to help instructors teach courses using this book. Solutions to exercises, figures from the book, lecture notes, lecture slides, and other materials are available to adopters from the publisher. Check the publisher's Web site for more information:

www.mkp.com/companions/1558606041

Concluding Remarks

If you read the following acknowledgments section, you will see that we went to great lengths to correct mistakes. Since a book goes through many printings, we have the opportunity to make even more corrections. If you uncover any remaining, resilient bugs, please contact the publisher by electronic mail at *cod3bugs@mkp.com* or by low-tech mail using the address found on the copyright page. The first person to report a technical error will be awarded a $1.00 bounty upon its implementation in future printings of the book!

This book is truly collaborative, despite one of us running a major university. Together we brainstormed about the ideas and method of presentation, then individually wrote about one-half of the chapters and acted as reviewer for every draft of the other half. The page count suggests we again wrote almost exactly the same number of pages. Thus, we equally share the blame for what you are about to read.

Acknowledgments for the Third Edition

We'd like to again express our appreciation to **Jim Larus** for his willingness in contributing his expertise on assembly language programming, as well as for welcoming readers of this book to use the simulator he developed and maintains. Our

exercise editor **Dan Sorin** took on the Herculean task of adding new exercises and answers. **Peter Ashenden** worked similarly hard to collect and organize the companion CD.

We are grateful to the many instructors who answered the publisher's surveys, reviewed our proposals, and attended focus groups to analyze and respond to our plans for this edition. They include the following individuals: Michael Anderson (University of Hartford), David Bader (University of New Mexico), Rusty Baldwin (Air Force Institute of Technology), John Barr (Ithaca College), Jack Briner (Charleston Southern University), Mats Brorsson (KTH, Sweden), Colin Brown (Franklin University), Lori Carter (Point Loma Nazarene University), John Casey (Northeastern University), Gene Chase (Messiah College), George Cheney (University of Massachusetts, Lowell), Daniel Citron (Jerusalem College of Technology, Israel), Albert Cohen (INRIA, France), Lloyd Dickman (PathScale), Jose Duato (Universidad Politécnica de Valencia, Spain), Ben Dugan (University of Washington), Derek Eager (University of Saskatchewan, Canada), Magnus Ekman (Chalmers University of Technology, Sweden), Ata Elahi (Southern Connecticut State University), Soundararajan Ezekiel (Indiana University of Pennsylvania), Ernest Ferguson (Northwest Missouri State University), Michael Fry (Lebanon Valley College, Pennsylvania), R. Gaede (University of Arkansas at Little Rock), Jean-Luc Gaudiot (University of California, Irvine), Thomas Gendreau (University of Wisconsin, La Crosse), George Georgiou (California State University, San Bernardino), Paul Gillard (Memorial University of Newfoundland, Canada), Joe Grimes (California Polytechnic State University, SLO), Max Hailperin (Gustavus Adolphus College), Jayantha Herath (St. Cloud State University, Minnesota), Mark Hill (University of Wisconsin, Madison), Michael Hsaio (Virginia Tech), Richard Hughey (University of California, Santa Cruz), Tony Jebara (Columbia University), Elizabeth Johnson (Xavier University), Peter Kogge (University of Notre Dame), Morris Lancaster (BAH), Doug Lawrence (University of Montana), David Lilja (University of Minnesota), Nam Ling (Santa Clara University, California), Paul Lum (Agilent Technologies), Stephen Mann (University of Waterloo, Canada), Diana Marculescu (Carnegie Mellon University), Margaret McMahon (U.S. Naval Academy Computer Science), Uwe Meyer-Baese (Florida State University), Chris Milner (University of Virginia), Tom Pittman (Southwest Baptist University), Jalel Rejeb (San Jose State University, California), Bill Siever (University of Missouri, Rolla), Kevin Skadron (University of Virginia), Pam Smallwood (Regis University, Colorado), K. Stuart Smith (Rocky Mountain College), William J. Taffe (Plymouth State University), Michael E. Thomodakis (Texas A&M University), Ruppa K. Thulasiram (University of Manitoba, Canada), Ye Tung (University of South Alabama), Steve VanderLeest (Calvin College), Neal R. Wagner (University of Texas at San Antonio), and Kent Wilken (University of California, Davis).

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To help us meet our goal of creating 70% new exercises and solutions for this edition, we recruited several graduate students recommended to us by their professors. We are grateful for their creativity and persistence: Michael Black (University of Maryland), Lei Chen (University of Rochester), Nirav Dave (Massachusetts Institute of Technology), Wael El Essawy (University of Rochester), Nikil Mehta (Brown University), Nicholas Nelson (University of Rochester), Aaron Smith (University of Texas, Austin), and Charlie Wang (Duke University).

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We wish to thank the extended Morgan Kaufmann family for agreeing to publish this book again under the able leadership of **Denise Penrose**. She developed the vision of the hybrid paper-CD book and recruited the many people above who played important roles in developing the book.

Simon Crump managed the book production process, and **Summer Block** coordinated the surveying of users and their responses. We thank also the many freelance vendors who contributed to this volume, especially **Nancy Logan** and **Dartmouth Publishing, Inc.**, our compositors.

The contributions of the nearly 100 people we mentioned here have made this third edition our best book yet. Enjoy!

David A. Patterson **John L. Hennessy**