教育部高等教育司推荐
国外优秀信息科学与技术系列教学用书

计算机组织与结构

——性能设计

（第五版　影印版）

COMPUTER ORGANIZATION AND ARCHITECTURE

Designing for Performance

(Fifth Edition)

William Stallings

高等教育出版社
Higher Education Press
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前　言

20 世纪末，以计算机和通信技术为代表的信息科学和技术，对世界的经济、军事、科技、教育、文化、卫生等方面的发展产生了深刻的影响，由此而兴起的信息产业已经成为世界经济发展的支柱。进入 21 世纪，各国为了加快本国的信息产业，加大了资金投入和政策扶持。

为了加快我国信息产业的进程，在我国《国民经济和社会发展第十个五年计划纲要》中，明确提出“以信息化带动工业化，发挥后发优势，实现社会生产力的跨越式发展。”信息产业的国际竞争将日趋激烈。在我国加入 WTO 后，我国信息产业将面临国外竞争对手的严峻挑战。竞争成败最终将取决于信息科学和技术人才的多少与优劣。

在 20 世纪末，我国信息产业虽然得到迅猛发展，但与国际先进国家相比，差距还很大。为了赶上并超过国际先进水平，我国必须加快信息技术人才的培养，特别要培养一大批具有国际竞争能力的高水平的信息技术人才，促进我国信息产业和国家信息化水平的全面提高。为此，教育部高等教育司根据教育部吕福源副部长的意见，在长期重视推动高等学校信息科学和技术教学的基础上，将实施超前发展战略，采取一些重要举措，加快推动高等学校的信息科学和技术等相关专业的教学工作。在大力宣传、推荐我国专家编著的面向 21 世纪和“九五”重点的信息科学和技术课程教材的基础上，在有条件的高等学校的某些信息科学和技术课程中推动使用国外优秀教材的影印版进行英语或双语教学，以缩短我国在计算机教学上与国际先进水平的差距，同时也有助于强化我国大学生的英语水平。

为了达到上述目的，在分析一些出版社已影印相关教材，一些学校已试用影印教材进行教学的基础上，教育部高等教育司组织并委托高等教育出版社开展国外优秀信息科学和技术优秀教材及其教学辅助材料的引进研究与影印出版的试点工作。为推动用影印版教材进行教学创造条件。

本次引进的系列教材的影印出版工作，是在对我国高校信息科学和技术专业的课程与美国高校的进行对比分析的基础上展开的；所影印出版的教材均由我国主要高校

的信息科学和技术专家组成的专家组，从国外近两年出版的大量最新教材中精心筛选评审通过的内容新、有影响的优秀教材；影印教材的定价原则上应与我国大学教材价格相当。

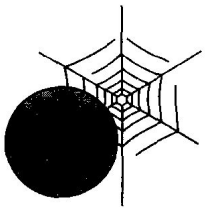
教育部高等教育司将此影印系列教材推荐给高等学校，希望有关教师选用，使用后有什么意见和建议请及时反馈。也希望有条件的出版社，根据影印教材的要求，积极参加此项工作，以便引进更多、更新、更好的外国教材和教学辅助材料。

同时，感谢国外有关出版公司对此项引进工作的配合，欢迎更多的国外公司关心并参与此项工作。

教育部高等教育司

二〇〇一年四月

For my great-hearted wife
ATS
and her constant companions Geoffroi
and Princesse Kate Lan Kinetic,
Les Enfants du Paradis



WEB SITE FOR COMPUTER ORGANIZATION AND ARCHITECTURE

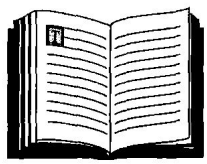
Fifth Edition

The Web site at http://www.shore.net/~ws/COA5e.html provides support for instructors and students using the book. It includes the following elements.

Course Support Materials

The course support materials include

- Copies of figures from the book in PDF format
- A detailed set of course notes in PDF format suitable for student handouts or for use as viewgraphs
- A set of PowerPoint slides for use as lecture aids
- An errata sheet for the book, updated at most monthly



COA Courses

The COA5e Web site includes links to Web sites for courses taught using the book. These sites can provide useful ideas about scheduling and topic ordering, as well as a number of useful handouts and other materials.

Useful Web Sites

The COA5e Web site includes links to relevant Web sites, organized by chapter. The links cover a broad spectrum of topics and will enable students to explore timely issues in greater depth.

Internet Mailing List

An Internet mailing list is maintained so that instructors using this book can exchange information, suggestions, and questions with each other and the author. Subscription information is provided at the Web site.

Simulation Tools

The Web site includes a link to the SimpleScalar Web site. This is a simulation tool that can be used to analyze an experiment with processor design issues. The site includes downloadable software and background information. The instructor's manual includes more information on loading and using the software and suggested student projects. See Appendix B for more information.

PREFACE

OBJECTIVES

This book is about the structure and function of computers. Its purpose is to present, as clearly and completely as possible, the nature and characteristics of modern-day computer systems.

This task is challenging for several reasons. First, there is a tremendous variety of products that can rightly claim the name of "computer", from single-chip microprocessors, costing a few dollars, to supercomputers, costing tens of millions of dollars. Variety is exhibited not only in cost, but in size, performance, and application. Second, the rapid pace of change that has always characterized computer technology continues with no letup. These changes cover all aspects of computer technology, from the underlying integrated circuit technology used to construct computer components, to the increasing use of parallel organization concepts in combining those components.

In spite of the variety and pace of change in the computer field, certain fundamental concepts apply consistently throughout. The application of these concepts depends on the current state of the technology and the price/performance objectives of the designer. The intent of this book is to provide a thorough discussion of the fundamentals of computer organization and architecture and to relate these to contemporary design issues.

The subtitle suggest the theme and the approach taken in this book. It has always been important to design computer systems to achieve high performance, but never has this requirement been stronger or more difficult to satisfy than today. All of the basic performance characteristics of computer systems, including processor speed, memory speed, memory capacity, and interconnection data rates, are increasing rapidly. Moreover, they are increasing at different rates. This makes it difficult to design a balanced system that maximizes the performance and utilization of all elements. Thus, computer design increasingly becomes a game of changing the structure or function in one area to compensate for a performance mismatch in another area. We will see this game played out in numerous design decisions throughout the book.

A computer system, like any system, consists of an interrelated set of components. The system is best characterized in terms of structure—the way in which components are interconnected, and function—the operation of the individual components. Furthermore, a computer's organization is hierarchic. Each major component can be further described by decomposing it into its major subcomponents and describing their structure and function. For clarity and ease of understanding, this hierarchical organization is described in this book from the top down:

- **Computer system:** Major components are processor, memory, I/O.
- **Processor:** Major components are control unit, registers, ALU, and instruction execution unit.
- **Control unit:** Major components are control memory, microinstruction sequencing logic, and registers.

The objective is to present the material in a fashion that keeps new material in a clear context. This should minimize the chance that the reader will get lost and should provide better motivation than a bottom-up approach.

Throughout the discussion, aspects of the system are viewed from the points of view of both architecture (those attributes of a system visible to a machine language programmer) and organization (the operational units and their interconnections that realize the architecture).

EXAMPLE SYSTEMS

Throughout this book, examples from a number of different machines are used to clarify and reinforce the concepts being presented. Many, but by no means all, of the examples are drawn from two computer families: the Intel Pentium II, and the PowerPC. (The recently introduced Pentium III is essentially the same as the Pentium II, with an expanded set of multimedia instructions.) These two systems together encompass most of the current computer design trends. The Pentium II is essentially a complex instruction set computer (CISC) with a RISC core, while the PowerPC is essentially a reduced-instruction set computer (RISC). Both systems make use of superscalar design principles and both support multiple processor configurations.

PLAN OF THE TEXT

The book is organized into five parts:

Part One—Overview: This part provides a preview and context for the remainder of the book.

Part Two—The computer system: A computer system consists of processor, memory, and I/O modules, plus the interconnections among these major com

ponents. With the exception of the processor, which is sufficiently complex to be explored in Part Three, this part examines each of these aspects in turn.

Part Three—The central processing unit: The CPU consists of a control unit, registers, the arithmetic and logic unit, the instruction execution unit, and the interconnections among these components. Architectural issues, such as instruction set design and data types, are covered. The part also looks at organizational issues, such as pipelining.

Part Four—The control unit: The control unit is that part of the processor that activates the various components of the processor. This part looks at the functioning of the control unit and its implementation using microprogramming.

Part Five—Parallel organization: This final part looks at some of the issues involved in multiple processor and vector processing organizations.

A more detailed, chapter-by-chapter summary appears at the end of Chapter 1.

INTERNET SERVICES FOR INSTRUCTORS AND STUDENTS

There is a Web site for this book that provides support for students and instructors. The site includes links to other relevant sites, transparency masters of figures in the book in PDF (Adobe Acrobat) format, and sign-up information for the book's Internet mailing list. The Web page is at http://www.shore.net/~ws/COA5e.html; see the section, "Web Site for this Book," preceding this Preface, for more information. An Internet mailing list has been set up so that instructors using this book can exchange information, suggestions, and questions with each other and with the author. As soon as typos or other errors are discovered, an errata list for this book will be available at http://www.shore.net/~ws.

PROJECTS FOR TEACHING COMPUTER ORGANIZATION AND ARCHITECTURE

For many instructors, an important component of a computer organization and architecture course is a project or set of projects by which the student gets hands-on experience to reinforce concepts from the text. This book provides an unparalleled degree of support for including a projects component in the course. The instructor's manual not only includes guidance on how to assign and structure the projects, but also includes a set of suggested projects that covers a broad range of topics from the text:

- **Research projects:** The manual includes series of research assignments that instruct the student to research a particular topic on the Web or in the literature and write a report.

- **Simulation projects:** The manual provides support for the use of the simulation package SimpleScalar, which can be used to explore computer organization and architecture design issues.
- **Reading/report assignments:** The manual includes a list of papers in the literature, one or more for each chapter, that can be assigned for the student to read and then write a short report.

See Appendix B for details.

WHAT'S NEW IN THE FIFTH EDITION

In the four years since the fourth edition of this book was published, the field has seen continued innovations and improvements. In this new edition, I try to capture these changes while maintaining a broad and comprehensive coverage of the entire field. To begin this process of revision, the fourth edition of this book was extensively reviewed by a number of professors who teach the subject. The result is that, in many places, the narrative has been clarified and tightened, and illustrations have been improved. Also, a number of new "field-tested" problems have been added.

Beyond these refinements to improve pedagogy and user friendliness, there have been substantive changes throughout the book. Roughly the same chapter organization has been retained, but much of the material has been revised and new material has been added. Some of the most noteworthy changes are the following:

- **Optical memory:** The material on optical memory has been expanded to include magneto-optical memory devices.
- **Superscalar design:** The chapter on superscalar design has been expanded, to include a more detailed discussion and two new examples, the UltraSparc II and the MIPS R10000.
- **Multimedia instruction set:** the MMX instruction set, used in the Pentium II and Pentium III, is examined.
- **Predicated execution and speculative loading:** This edition features a discussion of these recent concepts, which are central to the design of the new IA-64 architecture from Intel and Hewlett-Packard.
- **SMPs, clusters, and NUMA systems:** The chapter on parallel organization has been completely rewritten. It new includes detailed descriptions of and comparisons among symmetric multiprocessors (SMPs), clusters, and nonuniform memory access (NUMA) systems.
- **Expanded instructor support:** As mentioned previously, the book now provides extensive support for projects. Support provided by the book Web site has also been expanded.

ACKNOWLEDGMENTS

This new edition has benefited from review by a number of people, who gave generously of their time and expertise. The following people reviewed the second edition and made many helpful suggestions: Yew Pen-Chung of University of Minnesota; Yuval Tamir of UCLA; Arthur Werbner; Bina Ramamurthy of SUNY Buffalo; Kitty Niles of University of Minnesota; and Marcus Goncalves of Automation Research Corp. David Lambert of Intel reviewed the Pentium material. The following reviewed portions of the fifth edition manuscript: Jay Kubicky; Mike Albaugh of Atari Games; Tom Callaway of Silicon Graphics; James Stine of Lehigh University; Gabriel Dos Reis of Ecole Normale Superieure de Cachan; and Rick Thomas of Rutgers. Bernd Leppla at IBM Germany helped in my understanding of the IBM mainframe SMP strategy. Professor Cindy Norris of Appalachian State University contributed some homework problems.

ACRONYMS

ALU	Arithmetic and Logic Unit
ASCII	American Standards Code for Information Interchange
ANSI	American National Standards Institute
BCD	Binary Coded Decimal
CD	Compact Disk
CD-ROM	Compact Disk-Read Only Memory
CPU	Central Processing Unit
CISC	Complex Instruction Set Computer
DRAM	Dynamic Random-Access Memory
DMA	Direct Memory Access
EPIC	Explicitly Parallel Instruction Computing
EPROM	Erasable Programmable Read-Only Memory
EEPROM	Electrically Erasable Programmable Read-Only Memory
HLL	High-Level Language
I/O	Input/Output
IAR	Instruction Address Register
IC	Integrated Circuit
IEEE	Institute of Electrical and Electronics Engineers
ILP	Instruction-Level Parallelism
IR	Instruction Register
LRU	Least Recently Used
LSI	Large-Scale Integration
MAR	Memory Address Register
MBR	Memory Buffer Register
MESI	Modify-Exclusive-Shared-Invalid
MMU	Memory Management Unit
MSI	Medium-Scale Integration
NUMA	Nonuniform Memory Access
PC	Program Counter
PCI	Peripheral Component Interconnect
PROM	Programmable Read-Only Memory
PSW	Processor Status Word
PCB	Process Control Block
RAID	Redundant Array of Independent Disks
RALU	Register/Arithmetic Logic Unit
RAM	Random-Access Memory
RISC	Reduced Instruction Set Computer
ROM	Read-Only Memory
SCSI	Small Computer System Interface
SMP	Symmetric Multliprocessors
SRAM	Static Random-Access Memory
SSI	Small-Scale Integration
VLSI	Very Large-Scale Integration
VLWI	Very Long Instruction Word
WORM	Write-Only Read-Many

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CONTENTS