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

(第六版 影印版)

COMPUTER ORGANIZATION & ARCHITECTURE

Designing for Performance

(Sixth Edition)

■ William Stallings

PEARSON Prentice Hall

高等教育出版社
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藏书章

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William Stallings

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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经济、科技、军事、教育和文化等产生了深刻影响。信息科学技术的迅速普及和应用，带动了世界范围信息产业的蓬勃发展，为许多国家带来了丰厚的回报。

进入 21 世纪，尤其随着我国加入 WTO，信息产业的国际竞争将更加激烈。我国信息产业虽然在 20 世纪末取得了迅猛发展，但与发达国家相比，甚至与印度、爱尔兰等国家相比，还有很大差距。国家信息化的发展速度和信息产业的国际竞争能力，最终都将取决于信息科学技术人才的质量和数量。引进国外信息科学和技术优秀教材，在有条件的学校推动开展英语授课或双语教学，是教育部为加快培养大批高质量的信息技术人才采取的一项重要举措。

为此，教育部要求由高等教育出版社首先开展信息科学和技术教材的引进试点工作。同时提出了两点要求，一是要高水平，二是要低价格。在高等教育出版社和信息科学技术引进教材专家组的努力下，经过比较短的时间，第一批引进的 20 多种教材已经陆续出版。这套教材出版后受到了广泛的好评，其中有不少是世界信息科学技术领域著名专家、教授的经典之作和反映信息科学技术最新进展的优秀作品，代表了目前世界信息科学技术教育的一流水平，而且价格也是最优惠的，与国内同类自编教材相当。

这项教材引进工作是在教育部高等教育司和高教社的共同组织下，由国内信息科学技术领域的专家、教授广泛参与，在对大量国外教材进行多次遴选的基础上，参考了国内和国外著名大学相关专业的课程设置进行系统引进的。其中，John Wiley 公司出版的贝尔实验室信息科学研究中心副总裁 Silberschatz 教授的经典著作《操作系统概念》，是我们经过反复谈判，做了很多努力才得以引进的。William Stallings 先生曾编写了在美国深受欢迎的信息科学技术系列教材，其中有多种教材获得过美国教材和学术著作者协会颁发的计算机科学与工程教材奖，这批引进教材中就有他的两本著作。留美中国学者 Jiawei Han 先生的《数据挖掘》是该领域中具有里程碑意义的著作。由达特茅斯学院 Thomas Cormen 和麻省理工学院、哥伦比亚大学的几

位学者共同编著的经典著作《算法导论》，在经历了 11 年的锤炼之后于 2001 年出版了第二版。目前任教于美国 Massachusetts 大学的 James Kurose 教授，曾在美国三所高校先后 10 次获得杰出教师或杰出教学奖，由他主编的《计算机网络》出版后，以其体系新颖、内容先进而倍受欢迎。在努力降低引进教材售价方面，高等教育出版社做了大量和细致的工作。这套引进的教材体现了权威性、系统性、先进性和经济性等特点。

教育部也希望国内和国外的出版商积极参与此项工作，共同促进中国信息技术教育和信息产业的发展。我们在与外商的谈判工作中，不仅要坚定不移地引进国外最优秀的教材，而且还要千方百计地将版权转让费降下来，要让引进教材的价格与国内自编教材相当，让广大教师和学生负担得起。中国的教育市场巨大，外国出版公司和国内出版社要通过扩大发行数量取得效益。

在引进教材的同时，我们还应做好消化吸收，注意学习国外先进的教学思想和教学方法，提高自编教材的水平，使我们的教学和教材在内容体系上，在理论与实践的结合上，在培养学生的动手能力上能有较大的突破和创新。

目前，教育部正在全国 35 所高校推动示范性软件学院的建设和实施，这也是加快培养信息科学技术人才的重要举措之一。示范性软件学院要立足于培养具有国际竞争力的实用性软件人才，与国外知名高校或著名企业合作办学，以国内外著名 IT 企业为实践教学基地，聘请国内外知名教授和软件专家授课，还要率先使用引进教材开展教学。

我们希望通过这些举措，能在较短的时间，为我国培养一大批高质量的信息技术人才，提高我国软件人才的国际竞争力，促进我国信息产业的快速发展，加快推动国家信息化进程，进而带动整个国民经济的跨越式发展。

教育部高等教育司

二〇〇二年三月

此为试读，需要完整PDF请访问：www.ertongbook.com

原 版 前 言

目标

这是一本有关计算机结构和功能的书籍，旨在尽可能清晰而完整地介绍现代计算机系统的性质和特征。

这项任务很具挑战性，主要有如下几个方面的原因。第一，从价值几美元的单片机到价值几千万美元的超级计算机，有太多种类的产品都称为“计算机”。产品的多样性不仅体现在价格上，而且也体现在大小、性能和应用上。第二，快速的变化已成为持续不断发展的计算机技术的特征。这些变化涵盖了计算机技术的所有方面，从用于构造计算机部件的底层的集成电路技术，到日益广泛使用的将这些部件组合起来的并行组织概念。

尽管计算机领域存在多样性和变化的迅速性，但一些基本的概念却始终不变。这些概念的应用取决于技术的现状和设计人员的价格/性能目标。本书旨在深入讨论计算机组织和体系结构的基本原理，并应用这些原现解决当代计算机设计中的问题。

本书的副标题表明了本书的主题和所采用的方法。设计一个计算机系统以达到高性能的目的历来都很重要，但这一需求从未像当今这么强烈和难以满足。计算机系统的所有基本性能特征，包括处理器速度、存储器速度、存储容量和互连数据速率都在日益提高，但提高的幅度不相同，从而使设计一个平衡的系统，以实现性能最大化和最大限度地利用所有的部件变得十分困难。因此，计算机设计逐渐成为一种博奕：为补偿某方面的性能失配而改变另一方面的结构或功能。我们将会看到，这种博奕贯穿在书中的许多设计决策中。

与任何系统类似，计算机系统由一组相互关联的部件组成。用结构（部件的互连方式）和功能（各个部件的操作）这两个词最能描绘系统的特征。此外，计算机的组织是层次化的。每一个主要部件都可以通过将它分解为子部件来描述它的结构和功能。为了清楚且容易地理解这一点，本书采用自上而下的方式来描述这种层次结构：

- **计算机系统**：主要部件有处理器、存储器和 I/O。
- **处理器**：主要部件有控制器、寄存器、ALU 和指令执行单元。

- **控制器**：主要部件有控制存储器、微指令顺序逻辑和寄存器。

本书的目标是尽量以条理清晰的方式介绍这些内容，使读者不会迷茫，而且比自下而上的方式更能激发读者的兴趣。

本书从两个视角来研究系统的特征：体系结构（机器语言程序员可见的系统属性）和组织（实现体系结构的操作单元及其互连）。这种方法将贯穿于本书所有的讨论中。

范例

本书采用了多种不同机器的例子来阐述和巩固所提出的概念。大量例子，但不是全部，取自两种计算机系列：Intel Pentium 4 和 IBM/Motorola 的 PowerPC。这两种系统包含了当今大多数计算机的设计趋势。Pentium 4 基本上是一种复杂指令集计算机（CISC），但也有一些 RISC 的特征；而 PowerPC 则基本上是一种精简指令集计算机（RISC）。这两种系统都采用了超标量设计原理，而且都支持多处理器配置。

本书内容的安排

本书分为五个部分。

第一部分——概述：概括介绍本书的其余各部分的内容及其前后关系。

第二部分——计算机系统：包括处理器、存储器、I/O 模块以及这些部件的互连。除处理器因太复杂而放在第三部分中专门讨论外，这一部分将依次研究这些部件。

第三部分——中央处理器：CPU 包括一个控制器、寄存器、算术和逻辑部件、指令执行单元以及所有这些部件的连接。这一部分也讨论了如指令集设计、数据类型等体系结构问题以及如流水线技术等组织问题。

第四部分——控制器：控制器是处理器中驱动其余各个部件的部件。这一部分讨论控制器的功能及其使用微程序设计的实现。

第五部分——并行组织：最后这一部分研究多处理器及向量处理组织的一些问题。

本书还包括一个内容丰富的术语表、一个常用缩略语表以及一个参考书目。每一章都有课外作业、复习题、关键词表、深入阅读建议和推荐的 Web 站点。

每一部分的开头都提供了该部分中各章的概要。

读者对象

本书是为学术界人士或专业人士所编写的，可作为计算机科学、计算机工程或电子工程等专业的本科生的教材，可以讲授一个学期或两个学期。本书包含了 CS 220 Computer Architecture 的所有主题，这是 IEEE/ACM Computer Curricula 2001[JTF01]的核心科目之一。

对于那些对该领域有兴趣的专业人士，本书可作为一本基本的参考书，并适合自学。

面向教师和学生的 Internet 服务

本书有一个配套的 Web 站点，为教师和学生的提供支持。其中包括了与其他相关站点的链接。书中插图和表格的 PDF 格式副本以及本书 Internet 邮件列表的注册信息。Web 页网址为 WilliamStallings.com/COA6e.html，详细信息可参见本书 Preface（前言）之前的“Web Site for Computer Organization and Architecture，Sixth Edition”。已经建了一个 Internet 邮件列表，以方便使用本书的教师之间或与作者之间交换信息、建议和问题。一旦发现本书中有录排错误或其他错误，将在该站点刊登勘误表。此外，在 WilliamStallings.com/StudentSupport.html 上的计算机科学学生资源网站上，为学习计算机科学的学生和专业人士提供了文档、信息以及有用的链接。

本书的教学用项目

许多教师都清楚，项目训练是计算机组织与结构课程很重要的一部分，它可以使学生得到实践经验，以强化他们从书中学到的概念。为将项目部分列入课程中，本书提供了前所未有的支持。教师手册不仅包括如何分配和组织项目的指导，还包括了一组涵盖本书大部分主题的项目。

- **研究项目**：手册包括一系列课外作业，用于指导学生研究 Web 上或文献中的某个特定主题，并写出报告。
- **仿真项目**：手册提供了对使用两个仿真软件包的支持，其中 SimpleScalar 可用来研究计算机组织与结构的设计问题，SMPCache 为研究对称多处理器的高速缓存设计问题提供了强有力的教学工具。

- **阅读/报告作业**：手册包括了一个文献论文列表，每章有一篇或几篇，可以作为作业要求学生阅读并写出一个简要的报告。

关于项目的详细信息见附录 C。

第六版中新增的内容

在本书的第五版出版以来的 3 年中，这个领域的创新和改进并没有停止脚步。在此新版本中，我试图捕捉这些变化以保持对整个领域广泛而全面的介绍。在开始修订此书时，本书的第五版已从许多教这门课的教授那里得到大量的评论。此外，该领域的许多专业人士对各个章节也进行了评论。结果使许多地方的叙述更加清晰而紧凑，插图也得以改进。同时，还增加了许多新的“现场实验”（field-tested）题。

除了这些改进教学和对读者更为友好的细节外，全书有许多实质性的改变。全书基本上保留了同样的章节结构，但修改了其中许多细节，并增加了新的内容。其中最值得注意的改变如下。

- **IA-64Itanium 体系结构**：这种新的体系结构包含了一些重要的概念，如预测执行（predicated execution）和推测装入（speculative loading），本书用一章的篇幅来描述和分析这两个概念。
- **高速缓存**：高性能处理器的设计中，高速缓存是一个核心部件，高速缓存的设计变得愈加复杂。本书用一整章的篇幅来讨论这个问题。
- **光存储器**：有关光存储器的内容得到了扩充和更新。
- **高级 DRAM 结构**：新增了更多的内容来讨论这一主题，更新了关于 SDRAMR 和 DRAM 的讨论。
- **SMP、机群系统和 NUMA 系统**：关于并行组织的章节得到扩充和更新。
- **教师支持的扩充**：如前所述，本书提供了针对项目的广泛支持，本书 Web 站点所提供的支持也得以扩充。

致谢

本书从许多人的评论中受益匪浅，他们慷慨地贡献了他们的时间和专业知识。下面

这些专家审阅了全部或大部分手稿：Willis King(休斯敦大学)、Albert Heaney(加利福尼亚州立大学)、A. S. Pandya(佛罗里大亚特兰大大学)、Yaser Khalifa(北达科他大学)和Sanjeev Baskiyar(奥本大学)。

同样感谢那些为此书的单个章节提供详细技术评论的人们：Nicole Kaiyan、Terje Mathisen、Daniel M. Pressel、Jeff Deifik、Bill Todd、 Charlie Cassidy、Andy Isaacson、Alex Potemkin、Michael Spratte、Hatem Yassine、Grzegorz Mazur、 Alan Lehotsky、Jonathan Hall、Sophie Wilson、Alan Alexander、 David Vickers、Pete Smoot 和 Erik Seligman。

阿帕拉契州立大学的 Cindy Norris 教授贡献了一些课外作业题。

西班牙 Extremadura 大学的 Miguel Angel Vega Rodriguez 教授、Juan Manuel Sánchez Pérea 教授和 Juan Antonio Gómez Pulido 教授编写了教师手册中的 SMPCache 习题和 SMPCache 的用户指南。

威斯康星大学的 Todd Bezenek 和 Lehigh 大学的 James Stine 编写了教师手册中的 SimpleScalar 习题，Todd 同时也编写了 SimpleScalar 用户指南。

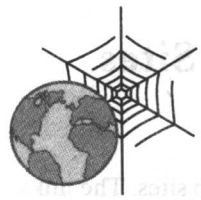
关于作者

William Stallings 为理解计算机网络和计算机体系结构的技术发展的全貌做出了非常重要的贡献。他编写了 17 本书，加上修订的版本，共有 35 本有关此类主题的不同方面的书。他连续 5 年获得美国教材和学术著作者协会颁发的计算机科学与工程最佳教材奖。

在过去的 25 年中，Stallings 博士在此领域已成为一个技术贡献者、技术经理和几个高技术公司的执行官。他是一个独立的顾问，客户包括计算机和网络制造商及消费者、软件开发公司和前沿的政府研究机构。他创办了并维护着计算机科学学生资源网站：

http://www.WilliamStallings.com/StudentSupport.html.

Stallings 博士从 MIT 获得计算机科学博士学位，从 Notre Dame 大学获得电气工程学士学位。



WEB SITE FOR COMPUTER ORGANIZATION AND ARCHITECTURE
Sixth Edition

The Web site at WilliamStallings.com/COA6e.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
- Copies of tables from the book in PDF format
- A set of PowerPoint slides for use as lecture aids
- A set of PDF course notes suitable for student handout or for use as viewgraphs
- Computer Science Student Resource Site: contains a number of links and documents that students may find useful in their ongoing computer science education. The site includes a review of basic, relevant mathematics; advice on research, writing, and doing homework problems; links to computer science research resources, such as report repositories and bibliographies; and other useful links
- 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.

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Useful Web Sites

The COA6e Web site includes links to relevant Web sites. 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 book's Web site.

Simulation Tools for COA Projects

The Web site includes links to the SimpleScalar and SMPCache Web sites. These are two software packages that serve as frameworks for project implementation. Each site includes downloadable software and background information. See Appendix C 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 suggests 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 hierarchical. 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, and 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

This book uses examples from a number of different machines 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 4, and the IBM/Motorola PowerPC. These two systems together encompass most of the current computer design trends. The Pentium 4 is essentially a complex instruction set computer (CISC) with some RISC features, 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 components. With the exception of the processor, which is sufficiently complex to be explored in Part Three, this part examines each of these elements 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. Part Three 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.

The book also includes an extensive glossary, a list of frequently used acronyms, and a bibliography. Each chapter includes homework problems, review questions, a list of key words, suggestions for further reading, and recommended Web sites.

A more detailed, chapter-by-chapter summary of each part appears at the beginning of that part.

INTENDED AUDIENCE

The book is intended for both an academic and a professional audience. As a textbook, it is intended as a one- or two-semester undergraduate course for computer science, computer engineering, and electrical engineering majors. It covers all the topics in *CS 220 Computer Architecture*, which is one of the core subject areas in the *IEEE/ACM Computer Curricula 2001* [JTF01].

For the professional interested in this field, the book serves as a basic reference volume and is suitable for self-study.

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, copies of the figures and tables from the book in PDF (Adobe Acrobat) format, and sign-up information for the book's Internet mailing list. The Web page is at WilliamStallings.com/COA6e.html; see the section, "Web Site for Computer Organization and Architecture, Sixth Edition", 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 WilliamStallings.com. In addition, the Computer Science Student Resource site, at WilliamStallings.com/StudentSupport.html, provides documents, information, and useful links for computer science students and professionals.

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 a series of 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 two simulation packages: SimpleScalar can be used to explore computer organization and architecture design issues. SMPCache provides a powerful educational tool for examining cache design issues for symmetric multiprocessors.
- **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 C for details.

WHAT'S NEW IN THE SIXTH EDITION

In the three years since the fifth 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 fifth edition of this book was extensively reviewed by a number of professors who teach the subject. In addition, a number of professionals working in the field reviewed individual chapters. 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:

- **IA-64/Itanium architecture:** This new architecture includes such important concepts as predicated execution and speculative loading. This edition features a chapter-length description and analysis.

- **Cache memory:** Cache memory is a central element in the design of high-performance processors, and cache design has become increasingly complex. An entire chapter is devoted to this issue in the new edition.
- **Optical memory:** The material on optical memory has been expanded and updated.
- **Advanced DRAM architecture:** More material has been added to cover this topic, including an updated discussion of SDRAM and RDRAM.
- **SMPs, clusters, and NUMA systems:** The chapter on parallel organization has been expanded and updated.
- **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 all or a large part of the manuscript: Willis King (University of Houston), Albert Heaney (California State University), A. S. Pandya (Florida Atlantic University), Yaser Khalifa (University of North Dakota), and Sanjeev Baskiyar (Auburn University).

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Professor Cindy Norris of Appalachian State University contributed some homework problems.

Professor Miguel Angel Vega Rodriguez, Prof. Dr. Juan Manuel Sánchez Pérez, and Prof. Dr. Juan Antonio Gómez Pulido, all of University of Extremadura, Spain prepared the SMPCache problems in the instructors manual and authored the SMPCache User's Guide.

Todd Bezenek of the University of Wisconsin and James Stine of Lehigh University prepared the SimpleScalar problems in the instructors manual, and Todd also authored the SimpleScalar User's Guide.

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