Computer Organization and Architecture

Designing for Performance

Ninth Edition

William Stallings

PEARSON

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To Tricia (ATS),
my loving wife, the kindest
and gentlest person

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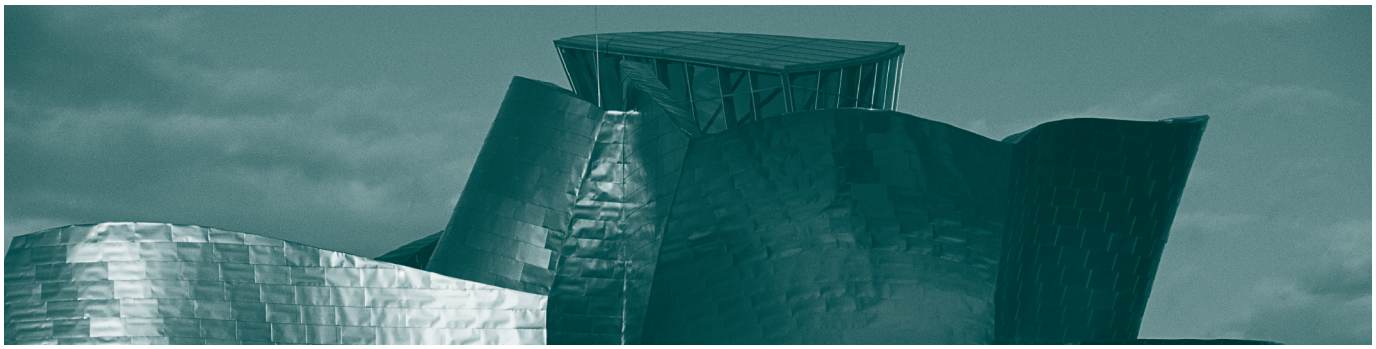
ONLINE APPENDICES

[1]Online chapters, appendices, and other documents are Premium Content, available via the access card at the front of this book.

ONLINE RESOURCES

Site	Location	Description
Companion Website	WilliamStallings.com/ ComputerOrganization	*Student Resources* link: Useful links and documents for students. *Instructor Resources* link: Useful links and documents for instructors.
Premium Content	Click on *Premium Content* link at Companion Website or at pearsonhighered.com/stallings and enter the student access code found on the card in the front of the book.	Online chapters, appendices, and other documents that supplement the book.
Instructor Resource Center (IRC)	Click on *Pearson Resources for Instructors* link at Companion Website or on *Instructor Resource* link at pearsonhighered.com/stallings.	Solutions manual, projects manual, slides, and other useful documents.
Computer Science Student Resource Site	ComputerScienceStudent.com	Useful links and documents for computer science students.



PREFACE

WHAT'S NEW IN THE NINTH EDITION

In the four years since the eighth 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 eighth edition of this book was extensively reviewed by a number of professors who teach the subject and by professionals working in the field. The result is that, in many places, the narrative has been clarified and tightened, and illustrations have been improved.

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. The most noteworthy changes are as follows:

- **Point-to-point interconnect:** The traditional bus architecture has increasingly been replaced with high-speed point-to-point interconnect schemes. A new section explores this technology, using Intel's QuickPath Interconnect (QPI) as an example.
- **PCI Express:** PCI Express (PCIe) has become a standard peripheral interconnect architecture, replacing PCI and other bus-based architectures. A new section covers PCIe.
- **Solid state drive and flash memory:** Solid state drives are increasingly displacing hard disk drives over a range of computers. A new section covers SSDs and the underlying flash memory technology.
- **IEEE 754 Floating-Point Standard:** The coverage of IEEE 754 has been updated to reflect the 2008 standard.
- **Contemporary mainframe organization:** Chapters 7 and 18 include sections on the zEnterprise 196, IBM's latest mainframe computer offering (at the time of this writing), introduced in 2010.
- **I/O standards:** The book has been updated to reflect the latest developments, including Thunderbolt.
- **Multicore architecture:** The material on multicore architecture has been expanded significantly.
- **Student study aids:** Each chapter now begins with a list of learning objectives.

- **Sample syllabus:** The text contains more material than can be conveniently covered in one semester. Accordingly, instructors are provided with several sample syllabi that guide the use of the text within limited time (e.g., 16 weeks or 12 weeks). These samples are based on real-world experience by professors with the eighth edition.
- **Test bank:** A set of review questions, including yes/no, multiple choice, and fill in the blank is provided for each chapter.

With each new edition it is a struggle to maintain a reasonable page count while adding new material. In part this objective is realized by eliminating obsolete material and tightening the narrative. For this edition, chapters and appendices that are of less general interest have been moved online, as individual PDF files. This has allowed an expansion of material without the corresponding increase in size and price.

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 also 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, I/O.
- **Processor:** Major components are control unit, registers, ALU, and instruction execution unit.
- **Control unit:** Provides control signals for the operation and coordination of all processor components. Traditionally, a microprogramming implementation has been used, in which major components are control memory, microinstruction sequencing logic, and registers. More recently, microprogramming has been less prominent but remains an important implementation technique.

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 text is intended to acquaint the reader with the design principles and implementation issues of contemporary operating systems. Accordingly, a purely conceptual or theoretical treatment would be inadequate. To illustrate the concepts and to tie them to real-world design choices that must be made, two processor families have been chosen as running examples:

- **Intel x86 architecture:** The x86 architecture is the most widely used for nonembedded computer systems. The x86 is essentially a complex instruction set computer (CISC) with some RISC features. Recent members of the x86 family make use of superscalar and multicore design principles. The evolution of features in the x86 architecture provides a unique case study of the evolution of most of the design principles in computer architecture.
- **ARM:** The ARM architecture is arguably the most widely used embedded processor, used in cell phones, iPods, remote sensor equipment, and many other devices. The ARM is essentially a reduced instruction set computer (RISC). Recent members of the ARM family make use of superscalar and multicore design principles.

Many, but by no means all, of the examples in this book are drawn from these two computer families. Numerous other systems, both contemporary and historical, provide examples of important computer architecture design features.

PLAN OF THE TEXT

The book is organized into six parts (see Chapter 0 for an overview):

- Overview
- The computer system

- Arithmetic and logic
- The central processing unit
- Parallel organization, including multicore
- The control unit

The book includes a number of pedagogic features, including the use of interactive simulations and numerous figures and tables to clarify the discussion. Each chapter includes a list of key words, review questions, homework problems, and suggestions for further reading. The book also includes an extensive glossary, a list of frequently used acronyms, and a bibliography.

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 core topics in the body of knowledge category, *Architecture and Organization*, in the *IEEE/ACM Computer Curriculum 2008: An Interim Revision to CS 2001*. This book also covers the core area *CE-CAO Computer Architecture and Organization* from the *IEEE/ACM Computer Engineering Curriculum Guidelines 2004*.

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

INSTRUCTOR SUPPORT MATERIALS

Support materials for instructors are available at the **Instructor Resource Center (IRC)** for this textbook, which can be reached through the Publisher's Website www.pearsonhighered.com/stallings or by clicking on the link labeled "Pearson Resources for Instructors" at this book's Companion Website at WilliamStallings.com/ComputerOrganization. To gain access to the IRC, please contact your local Pearson sales representative via pearsonhighered.com/educator/replocator/requestSalesRep.page or call Pearson Faculty Services at 1-800-526-0485. The IRC provides the following materials:

- **Projects manual:** Project resources including documents and portable software, plus suggested project assignments for all of the project categories listed subsequently in this Preface.
- **Solutions manual:** Solutions to end-of-chapter Review Questions and Problems.
- **PowerPoint slides:** A set of slides covering all chapters, suitable for use in lecturing.
- **PDF files:** Copies of all figures and tables from the book.
- **Test bank:** A chapter-by-chapter set of questions.
- **Sample syllabuses:** The text contains more material than can be conveniently covered in one semester. Accordingly, instructors are provided with several sample syllabuses that guide the use of the text within limited time. These samples are based on real-world experience by professors with the first edition.

The **Companion Website**, at WilliamStallings.com/ComputerOrganization (click on Instructor Resources link) includes the following:

- Links to Websites for other courses being taught using this book.
- Sign-up information for an Internet mailing list for instructors using this book to exchange information, suggestions, and questions with each other and with the author.

STUDENT RESOURCES

For this new edition, a tremendous amount of original supporting material for students has been made available online, at two Web locations. The **Companion Website**, at WilliamStallings.com/ComputerOrganization (click on Student Resources link), includes a list of relevant links organized by chapter and an errata sheet for the book.

Purchasing this textbook new grants the reader six months of access to the **Premium Content Site**, which includes the following materials:

- **Online chapters:** To limit the size and cost of the book, two chapters of the book are provided in PDF format. The chapters are listed in this book's table of contents.
- **Online appendices:** There are numerous interesting topics that support material found in the text but whose inclusion is not warranted in the printed text. A total of 13 appendices cover these topics for the interested student. The appendices are listed in this book's table of contents.
- **Homework problems and solutions:** To aid the student in understanding the material, a separate set of homework problems with solutions are available. Students can enhance their understanding of the material by working out the solutions to these problems and then checking their answers.
- **Key papers:** Several dozen papers from the professional literature, many hard to find, are provided for further reading.
- **Supporting documents:** A variety of other useful documents are referenced in the text and provided online.

Finally, I maintain the Computer Science Student Resource Site at **WilliamStallings.com/StudentSupport.html**.

PROJECTS AND OTHER STUDENT EXERCISES

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 support materials available through Prentice Hall not only includes guidance on how to assign and structure the projects but also includes a set of user's manuals for various project types plus specific assignments, all written especially for this book. Instructors can assign work in the following areas:

- **Interactive simulation assignments:** Described subsequently.

- **Research projects:** A series of research assignments that instruct the student to research a particular topic on the Internet and write a report.
- **Simulation projects:** The IRC 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.
- **Assembly language projects:** A simplified assembly language, CodeBlue, is used and assignments based on the popular Core Wars concept are provided.
- **Reading/report assignments:** 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.
- **Writing assignments:** A list of writing assignments to facilitate learning the material.
- **Test bank:** Includes T/F, multiple choice, and fill-in-the-blanks questions and answers.

This diverse set of projects and other student exercises enables the instructor to use the book as one component in a rich and varied learning experience and to tailor a course plan to meet the specific needs of the instructor and students. See Appendix A in this book for details.

INTERACTIVE SIMULATIONS

An important feature in this edition is the incorporation of interactive simulations. These simulations provide a powerful tool for understanding the complex design features of a modern computer system. A total of 20 interactive simulations are used to illustrate key functions and algorithms in computer organization and architecture design. At the relevant point in the book, an icon indicates that a relevant interactive simulation is available online for student use. Because the animations enable the user to set initial conditions, they can serve as the basis for student assignments. The instructor's supplement includes a set of assignments, one for each of the animations. Each assignment includes several specific problems that can be assigned to students. For access to the animations, click on the rotating globe at this book's Website at http://williamstallings.com/ComputerOrganization.

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Aswin Sreedhar of the University of Massachusetts developed the interactive simulation assignments and also wrote the test bank.

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About the Author

Dr. William Stallings has made a unique contribution to understanding the broad sweep of technical developments in computer security, computer networking and computer architecture. He has authored 17 titles, and counting revised editions, a total of 42 books on various aspects of these subjects. His writings have appeared in numerous ACM and IEEE publications, including the *Proceedings of the IEEE* and *ACM Computing Reviews*.

He has 10 times received the award for the best Computer Science textbook of the year from the Text and Academic Authors Association.

In over 30 years in the field, he has been a technical contributor, technical manager, and an executive with several high-technology firms. He has designed and implemented both TCP/IP-based and OSI-based protocol suites on a variety of computers and operating systems, ranging from microcomputers to mainframes. As a consultant, he has advised government agencies, computer and software vendors, and major users on the design, selection, and use of networking software and products.

He created and maintains the **Computer Science Student Resource Site** at WilliamStallings.com/StudentSupport.html. This site provides documents and links on a variety of subjects of general interest to computer science students (and professionals). He is a member of the editorial board of Cryptologia, a scholarly journal devoted to all aspects of cryptology.

Dr. Stallings holds a PhD from M.I.T. in Computer Science and a B.S. from Notre Dame in electrical engineering.