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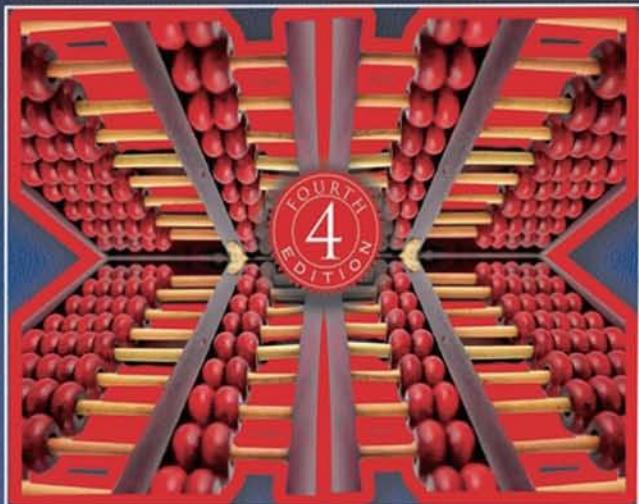
加州大学伯克利分校

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(英文版·第4版)

COMPUTER ORGANIZATION AND DESIGN

THE HARDWARE / SOFTWARE INTERFACE



机械工业出版社
China Machine Press



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DAVID A. PATTERSON
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计算机组成与设计 硬件/软件接口

(英文版 · 第4版)

Computer Organization and Design, The
Hardware/Software Interface, Fourth Edition

David A. Patterson
加州大学伯克利分校 著
(美) John L. Hennessy
斯坦福大学

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Computer Organization and Design, The Hardware/Software Interface, Fourth Edition

David A. Patterson and John L. Hennessy

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出版者的话

文艺复兴以降，源远流长的科学精神和逐步形成的学术规范，使西方国家在自然科学的各个领域取得了垄断性的优势；也正是这样的传统，使美国在信息技术发展的六十多年间名家辈出、独领风骚。在商业化的进程中，美国的产业界与教育界越来越紧密地结合，计算机学科中的许多泰山北斗同时身处科研和教学的最前线，由此而产生的经典科学著作，不仅擘划了研究的范畴，还揭示了学术的源变，既遵循学术规范，又自有学者个性，其价值并不会因年月的流逝而减退。

近年，在全球信息化大潮的推动下，我国的计算机产业发展迅猛，对专业人才的需求日益迫切。这对计算机教育界和出版界都既是机遇，也是挑战；而专业教材的建设在教育战略上显得举足轻重。在我国信息技术发展时间较短的现状下，美国等发达国家在其计算机科学发展的几十年间积淀和发展的经典教材仍有许多值得借鉴之处。因此，引进一批国外优秀计算机教材将对我国计算机教育事业的发展起到积极的推动作用，也是与世界接轨、建设真正世界一流大学的必由之路。

机械工业出版社华章公司较早意识到“出版要为教育服务”。自1998年开始，我们就将工作重点放在了遴选、移译国外优秀教材上。经过多年的不懈努力，我们与 Pearson, McGraw-Hill, Elsevier, MIT, John Wiley & Sons, Cengage 等世界著名出版公司建立了良好的合作关系，从他们现有的数百种教材中甄选出 Andrew S. Tanenbaum, Bjarne Stroustrup, Brian W. Kernighan, Dennis Ritchie, Jim Gray, Alfred V. Aho, John E. Hopcroft, Jeffrey D. Ullman, Abraham Silberschatz, William Stallings, Donald E. Knuth, John L. Hennessy, Larry L. Peterson 等大师名家的一批经典作品，以“计算机科学丛书”为总称出版，供读者学习、研究及珍藏。大理石纹理的封面，也正体现了这套丛书的品位和格调。

“计算机科学丛书”的出版工作得到了国内外学者的鼎力襄助，国内的专家不仅提供了中肯的选题指导，还不辞劳苦地担任了翻译和审校的工作；而原书的作者也相当关注其作品在中国的传播，有的还专程为其书的中译本作序。迄今，“计算机科学丛书”已经出版了近两百个品种，这些书籍在读者中树立了良好的口碑，并被许多高校采用为正式教材和参考书籍。其影印版“经典原版书库”作为姊妹篇也被越来越多实施双语教学的学校所采用。

权威的作者、经典的教材、一流的译者、严格的审校、精细的编辑，这些因素使我们的图书有了质量的保证。随着计算机科学与技术专业学科建设的不断完善和教材改革的逐渐深化，教育界对国外计算机教材的需求和应用都将步入一个新的阶段，我们的目标是尽善尽美，而反馈的意见正是我们达到这一终极目标的重要帮助。华章公司欢迎老师和读者对我们的工作提出建议或给予指正，我们的联系方法如下：

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华章科技图书出版中心

In Praise of Computer Organization and Design: The Hardware/Software Interface, Fourth Edition

“Patterson and Hennessy not only improve the pedagogy of the traditional material on pipelined processors and memory hierarchies, but also greatly expand the multiprocessor coverage to include emerging multicore processors and GPUs. The fourth edition of *Computer Organization and Design* sets a new benchmark against which all other architecture books must be compared.”

—David A. Wood, *University of Wisconsin-Madison*

“Patterson and Hennessy have greatly improved what was already the gold standard of textbooks. In the rapidly evolving field of computer architecture, they have woven an impressive number of recent case studies and contemporary issues into a framework of time-tested fundamentals.”

—Fred Chong, *University of California at Santa Barbara*

“Since the publication of the first edition in 1994, *Computer Organization and Design* has introduced a generation of computer science and engineering students to computer architecture. Now, many of those students have become leaders in the field. In academia, the tradition continues as faculty use the latest edition of the book that inspired them to engage the next generation. With the fourth edition, readers are prepared for the next era of computing.”

—David I. August, *Princeton University*

“The new coverage of multiprocessors and parallelism lives up to the standards of this well-written classic. It provides well-motivated, gentle introductions to the new topics, as well as many details and examples drawn from current hardware.”

—John Greiner, *Rice University*

“As computer hardware architecture moves from uniprocessor to multicores, the parallel programming environments used to take advantage of these cores will be a defining challenge to the success of these new systems. In the multicore systems, the interface between the hardware and software is of particular importance. This new edition of *Computer Organization and Design* is mandatory for any student who wishes to understand multicore architecture including the interface between programming it and its architecture.”

—Jesse Fang, *Director of Programming System Lab at Intel*

“The fourth edition of *Computer Organization and Design* continues to improve the high standards set by the previous editions. The new content, on trends that are reshaping computer systems including multicores, Flash memory, GPUs, etc., makes this edition a must read—even for all of those who grew up on previous editions of the book.”

—Parthasarathy Ranganathan, *Principal Research Scientist, HP Labs*

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 recent switch from uniprocessor to multicore microprocessors confirmed the soundness of this perspective, given since the first edition. While programmers could ignore the advice and rely on computer architects, compiler writers, and silicon engineers to make their programs run faster without change, that era is over. For programs to run faster, they must become parallel. While the goal of many researchers is to make it possible for programmers to be unaware of the underlying parallel nature of the hardware they are programming, it will take many years to realize this vision. Our view is that for at least the next decade, most programmers are going to have to understand the hardware/software interface if they want programs to run efficiently on parallel 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 often called Patterson and Hennessy.) Our motivation in writing the earlier book was to describe the principles of computer architecture using solid engineering fundamentals and quantitative cost/performance tradeoffs. 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 was intended for the serious computing professional who wanted a detailed understanding of computers.

A majority of the readers for this book do not plan to become computer architects. The performance and energy efficiency 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 Fourth Edition

We had five major goals for the fourth edition of *Computer Organization and Design*: given the multicore revolution in microprocessors, highlight parallel hardware and software topics throughout the book; streamline the existing material to make room for topics on parallelism; enhance pedagogy in general; update the technical content to reflect changes in the industry since the publication of the third edition in 2004; and restore the usefulness of exercises in this Internet age.

Before discussing the goals in detail, let's look at the table on the next page. It shows the hardware and software paths through the material. Chapters 1, 4, 5, and 7 are found on both paths, no matter what the experience or the focus. Chapter 1 is a new introduction that includes a discussion on the importance of power and how it motivates the switch from single core to multicore microprocessors. It also includes performance and benchmarking material that was a separate chapter in the third edition. Chapter 2 is likely to be review material for the hardware-oriented, but it is essential reading for the software-oriented, especially for those readers interested in learning more about compilers and object-oriented programming

<i>Chapter or appendix</i>	<i>Sections</i>	<i>Software focus</i>	<i>Hardware focus</i>
1. Computer Abstractions and Technology	1.1 to 1.9  1.10 (History)	 	 
2. Instructions: Language of the Computer	2.1 to 2.14  2.15 (Compilers & Java) 2.16 to 2.19  2.20 (History)	   	   
E. RISC Instruction-Set Architectures	 E.1 to E.19		
3. Arithmetic for Computers	3.1 to 3.9  3.10 (History)	 	 
C. The Basics of Logic Design	 C.1 to C.13		
4. The Processor	4.1 (Overview) 4.2 (Logic Conventions) 4.3 to 4.4 (Simple Implementation) 4.5 (Pipelining Overview) 4.6 (Pipelined Datapath) 4.7 to 4.9 (Hazards, Exceptions) 4.10 to 4.11 (Parallel, Real Stuff)  4.12 (Verilog Pipeline Control) 4.13 to 4.14 (Fallacies)  4.15 (History)	           	         
D. Mapping Control to Hardware	 D.1 to D.6		
5. Large and Fast: Exploiting Memory Hierarchy	5.1 to 5.8  5.9 (Verilog Cache Controller) 5.10 to 5.12  5.13 (History)	   	   
6. Storage and Other I/O Topics	6.1 to 6.10  6.11 (Networks) 6.12 to 6.13  6.14 (History)	   	   
7. Multicores, Multiprocessors, and Clusters	7.1 to 7.13  7.14 (History)	   	   
A. Graphics Processor Units	A.1 to A.12	 	 
B. Assemblers, Linkers, and the SPIM Simulator	B.1 to B.12	 	 

Read carefully



Read if have time



Reference



Review or read



Read for culture



languages. It includes material from Chapter 3 in the third edition so that the complete MIPS architecture is now in a single chapter, minus the floating-point instructions. Chapter 3 is for readers interested in constructing a datapath or in learning more about floating-point arithmetic. Some will skip Chapter 3, either because they don't need it or because it is a review. Chapter 4 combines two chapters from the third edition to explain pipelined processors. Sections 4.1, 4.5, and 4.10 give overviews for those with a software focus. Those with a hardware focus, however, will find that this chapter presents core material; they may also, depending on their background, want to read Appendix C on logic design first. Chapter 6 on storage is critical to readers with a software focus, and should be read by others if time permits. The last chapter on multicores, multiprocessors, and clusters is mostly new content and should be read by everyone.

The first goal was to make parallelism a first class citizen in this edition, as it was a separate chapter on the CD in the last edition. The most obvious example is Chapter 7. In particular, this chapter introduces the Roofline performance model, and shows its value by evaluating four recent multicore architectures on two kernels. This model could prove to be as insightful for multicore microprocessors as the 3Cs model is for caches.

Given the importance of parallelism, it wasn't wise to wait until the last chapter to talk about, so there is a section on parallelism in each of the preceding six chapters:

- *Chapter 1: Parallelism and Power.* It shows how power limits have forced the industry to switch to parallelism, and why parallelism helps.
- *Chapter 2: Parallelism and Instructions: Synchronization.* This section discusses locks for shared variables, specifically the MIPS instructions Load Linked and Store Conditional.
- *Chapter 3: Parallelism and Computer Arithmetic: Floating-Point Associativity.* This section discusses the challenges of numerical precision and floating-point calculations.
- *Chapter 4: Parallelism and Advanced Instruction-Level Parallelism.* It covers advanced ILP—superscalar, speculation, VLIW, loop-unrolling, and OOO—as well as the relationship between pipeline depth and power consumption.
- *Chapter 5: Parallelism and Memory Hierarchies: Cache Coherence.* It introduces coherency, consistency, and snooping cache protocols.
- *Chapter 6: Parallelism and I/O: Redundant Arrays of Inexpensive Disks.* It describes RAID as a parallel I/O system as well as a highly available ICO system.

Chapter 7 concludes with reasons for optimism why this foray into parallelism should be more successful than those of the past.

I am particularly excited about the addition of an appendix on Graphical Processing Units written by NVIDIA’s chief scientist, David Kirk, and chief architect, John Nickolls. Appendix A is the first in-depth description of GPUs, which is a new and interesting thrust in computer architecture. The appendix builds upon the parallel themes of this edition to present a style of computing that allows the programmer to think MIMD yet the hardware tries to execute in SIMD-style whenever possible. As GPUs are both inexpensive and widely available—they are even found in many laptops—and their programming environments are freely available, they provide a parallel hardware platform that many could experiment with.

The second goal was to streamline the book to make room for new material in parallelism. The first step was simply going through all the paragraphs accumulated over three editions with a fine-toothed comb to see if they were still necessary. The coarse-grained changes were the merging of chapters and dropping of topics. Mark Hill suggested dropping the multicycle processor implementation and instead adding a multicycle cache controller to the memory hierarchy chapter. This allowed the processor to be presented in a single chapter instead of two, enhancing the processor material by omission. The performance material from a separate chapter in the third edition is now blended into the first chapter.

The third goal was to improve the pedagogy of the book. Chapter 1 is now meatier, including performance, integrated circuits, and power, and it sets the stage for the rest of the book. Chapters 2 and 3 were originally written in an evolutionary style, starting with a “single celled” architecture and ending up with the full MIPS architecture by the end of Chapter 3. This leisurely style is not a good match to the modern reader. This edition merges all of the instruction set material for the integer instructions into Chapter 2—making Chapter 3 optional for many readers—and each section now stands on its own. The reader no longer needs to read all of the preceding sections. Hence, Chapter 2 is now even better as a reference than it was in prior editions. Chapter 4 works better since the processor is now a single chapter, as the multicycle implementation is a distraction today. Chapter 5 has a new section on building cache controllers, along with a new CD section containing the Verilog code for that cache.

The accompanying CD-ROM introduced in the third edition allowed us to reduce the cost of the book by saving pages as well as to go into greater depth on topics that were of interest to some but not all readers. Alas, in our enthusiasm to save pages, readers sometimes found themselves going back and forth between the CD and book more often than they liked. This should not be the case in this edition. Each chapter now has the Historical Perspectives section on the CD and four chapters also have one advanced material section on the CD. Additionally, all exercises are in the printed book, so flipping between book and CD should be rare in this edition.

For those of you who wonder why we include a CD-ROM with the book, the answer is simple: the CD contains content that we feel should be easily and immediately accessible to the reader no matter where they are. If you are interested in the advanced content, or would like to review a VHDL tutorial (for example), it is on the CD, ready for you to use. The CD-ROM also includes a feature that should greatly enhance your study of the material: a search engine is included that allows you to search for any string of text, in the printed book or on the CD itself. If you are hunting for content that may not be included in the book's printed index, you can simply enter the text you're searching for and the page number it appears on will be displayed in the search results. This is a very useful feature that we hope you make frequent use of as you read and review the book.

This is a fast-moving field, and as is always the case for our new editions, an important goal is to update the technical content. The AMD Opteron X4 model 2356 (code named "Barcelona") serves as a running example throughout the book, and is found in Chapters 1, 4, 5, and 7. Chapters 1 and 6 add results from the new power benchmark from SPEC. Chapter 2 adds a section on the ARM architecture, which is currently the world's most popular 32-bit ISA. Chapter 5 adds a new section on Virtual Machines, which are resurging in importance. Chapter 5 has detailed cache performance measurements on the Opteron X4 multicore and a few details on its rival, the Intel Nehalem, which will not be announced until after this edition is published. Chapter 6 describes Flash Memory for the first time as well as a remarkably compact server from Sun, which crams 8 cores, 16 DIMMs, and 8 disks into a single 1U bit. It also includes the recent results on long-term disk failures. Chapter 7 covers a wealth of topics regarding parallelism—including multithreading, SIMD, vector, GPUs, performance models, benchmarks, multiprocessor networks—and describes three multicores plus the Opteron X4: Intel Xeon model e5345 (Clovertown), IBM Cell model QS20, and the Sun Microsystems T2 model 5120 (Niagara 2).

The final goal was to try to make the exercises useful to instructors in this Internet age, for homework assignments have long been an important way to learn material. Alas, answers are posted today almost as soon as the book appears. We have a two-part approach. First, expert contributors have worked to develop entirely new exercises for each chapter in the book. Second, most exercises have a qualitative description supported by a table that provides several alternative quantitative parameters needed to answer this question. The sheer number plus flexibility in terms of how the instructor can choose to assign variations of exercises will make it hard for students to find the matching solutions online. Instructors will also be able to change these quantitative parameters as they wish, again frustrating those students who have come to rely on the Internet to provide solutions for a static and unchanging set of exercises. We feel this new approach is a valuable new addition to the book—please let us know how well it works for you, either as a student or instructor!

We have preserved useful book elements from prior editions. To make the book work better as a reference, we still place definitions of new terms in the margins at their first occurrence. The book element called “Understanding Program Performance” sections helps readers understand the performance of their programs and how to improve it, just as the “Hardware/Software Interface” book element helped readers understand the tradeoffs at this interface. “The Big Picture” section remains so that the reader sees the forest even despite all the trees. “Check Yourself” sections help readers to confirm their comprehension of the material on the first time through with answers provided at the end of each chapter. This edition also includes the green MIPS reference card, which was inspired by the “Green Card” of the IBM System/360. The removable card has been updated and should be a handy reference when writing MIPS assembly language programs.

Instructor Support

We have collected a great deal of material to help instructors teach courses using this book. Solutions to exercises, chapter quizzes, 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:

textbooks.elsevier.com/9780123744937

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 *cod4bugs@mfp.com* or by low-tech mail using the address found on the copyright page.

This edition marks a break in the long-standing collaboration between Hennessy and Patterson, which started in 1989. The demands of running one of the world’s great universities meant that President Hennessy could no longer make the substantial commitment to create a new edition. The remaining author felt like a juggler who had always performed with a partner who suddenly is thrust on the stage as a solo act. Hence, the people in the acknowledgments and Berkeley colleagues played an even larger role in shaping the contents of this book. Nevertheless, this time around there is only one author to blame for the new material in what you are about to read.

Acknowledgments for the Fourth Edition

I’d like to thank David Kirk, John Nickolls, and their colleagues at NVIDIA (Michael

Garland, John Montrym, Doug Voorhies, Lars Nyland, Erik Lindholm, Paulius Micikevicius, Massimiliano Fatica, Stuart Oberman, and Vasily Volkov) for writing the first in-depth appendix on GPUs. I'd like to express again my appreciation to **Jim Larus** of Microsoft Research 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.

I am also very grateful for the contributions of the many experts who developed the new exercises for this new edition. Writing good exercises is not an easy task, and each contributor worked long and hard to develop problems that are both challenging and engaging:

- *Chapter 1: Javier Bruguera* (Universidade de Santiago de Compostela)
- *Chapter 2: John Oliver* (Cal Poly, San Luis Obispo), with contributions from **Nicole Kaiyan** (University of Adelaide) and **Milos Prvulovic** (Georgia Tech)
- *Chapter 3: Matthew Farrens* (University of California, Davis)
- *Chapter 4: Milos Prvulovic* (Georgia Tech)
- *Chapter 5: Jichuan Chang, Jacob Leverich, Kevin Lim, and Partha Ranganathan* (all from Hewlett-Packard), with contributions from Nicole Kaiyan (University of Adelaide)
- *Chapter 6: Perry Alexander* (The University of Kansas)
- *Chapter 7: David Kaeli* (Northeastern University)

Peter Ashenden took on the Herculean task of editing and evaluating *all* of the new exercises. Moreover, he even added the substantial burden of developing the companion CD and new lecture slides.

Thanks to **David August** and **Prakash Prabhu** of Princeton University for their work on the chapter quizzes that are available for instructors on the publisher's Web site.

I relied on my Silicon Valley colleagues for much of the technical material that this book relies upon:

- AMD—for the details and measurements of the Opteron X4 (Barcelona): **William Brantley**, **Vasileios Liaskovitis**, **Chuck Moore**, and **Brian Waldecker**.
- Intel—for the prereleased information on the Intel Nehalem: **Faye Briggs**.
- Micron—for background on Flash Memory in Chapter 6: **Dean Klein**.
- Sun Microsystems—for the measurements of the instruction mixes for the SPEC2006 benchmarks in Chapter 2 and details and measurements of the Sun Server x4150 in Chapter 6: **Yan Fisher**, **John Fowler**, **Darryl Gove**, **Paul**

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The contributions of the nearly 200 people we mentioned here have helped make this fourth edition what I hope will be our best book yet. Enjoy!

David A. Patterson



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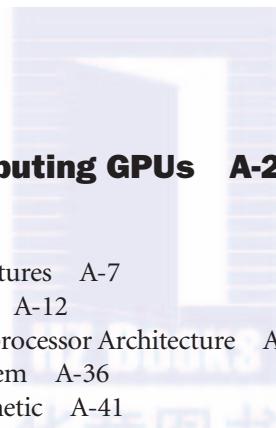
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Civilization advances by extending the number of important operations which we can perform without thinking about them.

Alfred North Whitehead

An Introduction to Mathematics, 1911

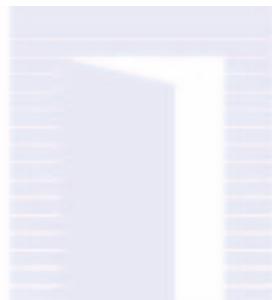
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1.1

Introduction



Welcome to this book! We're delighted to have this opportunity to convey the excitement of the world of computer systems. This is not a dry and dreary field, where progress is glacial and where new ideas atrophy from neglect. No! Computers are the product of the incredibly vibrant information technology industry, all aspects of which are responsible for almost 10% of the gross national product of the United States, and whose economy has become dependent in part on the rapid improvements in information technology promised by Moore's law. This unusual industry embraces innovation at a breathtaking rate. In the last 25 years, there have been a number of new computers whose introduction appeared to revolutionize the computing industry; these revolutions were cut short only because someone else built an even better computer.

This race to innovate has led to unprecedented progress since the inception of electronic computing in the late 1940s. Had the transportation industry kept pace with the computer industry, for example, today we could travel from New York to London in about a second for roughly a few cents. Take just a moment to contemplate how such an improvement would change society—living in Tahiti while working in San Francisco, going to Moscow for an evening at the Bolshoi Ballet—and you can appreciate the implications of such a change.

Computers have led to a third revolution for civilization, with the information revolution taking its place alongside the agricultural and the industrial revolutions. The resulting multiplication of humankind's intellectual strength and reach naturally has affected our everyday lives profoundly and changed the ways in which the search for new knowledge is carried out. There is now a new vein of scientific investigation, with computational scientists joining theoretical and experimental scientists in the exploration of new frontiers in astronomy, biology, chemistry, and physics, among others.

The computer revolution continues. Each time the cost of computing improves by another factor of 10, the opportunities for computers multiply. Applications that were economically infeasible suddenly become practical. In the recent past, the following applications were "computer science fiction."

- *Computers in automobiles:* Until microprocessors improved dramatically in price and performance in the early 1980s, computer control of cars was ludicrous. Today, computers reduce pollution, improve fuel efficiency via engine controls, and increase safety through the prevention of dangerous skids and through the inflation of air bags to protect occupants in a crash.
- *Cell phones:* Who would have dreamed that advances in computer systems would lead to mobile phones, allowing person-to-person communication almost anywhere in the world?
- *Human genome project:* The cost of computer equipment to map and analyze human DNA sequences is hundreds of millions of dollars. It's unlikely that anyone would have considered this project had the computer costs been 10 to 100 times higher, as they would have been 10 to 20 years ago. Moreover, costs continue to drop; you may be able to acquire your own genome, allowing medical care to be tailored to you.
- *World Wide Web:* Not in existence at the time of the first edition of this book, the World Wide Web has transformed our society. For many, the WWW has replaced libraries.
- *Search engines:* As the content of the WWW grew in size and in value, finding relevant information became increasingly important. Today, many people rely on search engines for such a large part of their lives that it would be a hardship to go without them.

Clearly, advances in this technology now affect almost every aspect of our society. Hardware advances have allowed programmers to create wonderfully useful software, which explains why computers are omnipresent. Today's science fiction suggests tomorrow's killer applications: already on their way are virtual worlds, practical speech recognition, and personalized health care.

Classes of Computing Applications and Their Characteristics

Although a common set of hardware technologies (see Sections 1.3 and 1.7) is used in computers ranging from smart home appliances to cell phones to the largest supercomputers, these different applications have different design requirements and employ the core hardware technologies in different ways. Broadly speaking, computers are used in three different classes of applications.

Desktop computers are possibly the best-known form of computing and are characterized by the personal computer, which readers of this book have likely used extensively. Desktop computers emphasize delivery of good performance to single users at low cost and usually execute third-party software. The evolution of many computing technologies is driven by this class of computing, which is only about 30 years old!

Servers are the modern form of what were once mainframes, minicomputers, and supercomputers, and are usually accessed only via a network. Servers are oriented to carrying large workloads, which may consist of either single complex applications—usually a scientific or engineering application—or handling many small jobs, such as would occur in building a large Web server. These applications are usually based on software from another source (such as a database or simulation system), but are often modified or customized for a particular function. Servers are built from the same basic technology as desktop computers, but provide for greater expandability of both computing and input/output capacity. In general, servers also place a greater emphasis on dependability, since a crash is usually more costly than it would be on a single-user desktop computer.

Servers span the widest range in cost and capability. At the low end, a server may be little more than a desktop computer without a screen or keyboard and cost a thousand dollars. These low-end servers are typically used for file storage, small business applications, or simple Web serving (see Section 6.10). At the other extreme are **supercomputers**, which at the present consist of hundreds to thousands of processors and usually **terabytes** of memory and **petabytes** of storage, and cost millions to hundreds of millions of dollars. Supercomputers are usually used for high-end scientific and engineering calculations, such as weather forecasting, oil exploration, protein structure determination, and other large-scale problems. Although such supercomputers represent the peak of computing capability, they represent a relatively small fraction of the servers and a relatively small fraction of the overall computer market in terms of total revenue.

Although not called supercomputers, Internet **datacenters** used by companies like eBay and Google also contain thousands of processors, terabytes of memory, and petabytes of storage. These are usually considered as large clusters of computers (see Chapter 7).

Embedded computers are the largest class of computers and span the widest range of applications and performance. Embedded computers include the

desktop computer A computer designed for use by an individual, usually incorporating a graphics display, a keyboard, and a mouse.

server A computer used for running larger programs for multiple users, often simultaneously, and typically accessed only via a network.

supercomputer A class of computers with the highest performance and cost; they are configured as servers and typically cost millions of dollars.

terabyte Originally 1,099,511,627,776 (2^{40}) bytes, although some communications and secondary storage systems have redefined it to mean 1,000,000,000,000 (10^{12}) bytes.

petabyte Depending on the situation, either 1000 or 1024 terabytes.

datacenter A room or building designed to handle the power, cooling, and networking needs of a large number of servers.

embedded computer A computer inside another device used for running one predetermined application or collection of software.

microprocessors found in your car, the computers in a cell phone, the computers in a video game or television, and the networks of processors that control a modern airplane or cargo ship. Embedded computing systems are designed to run one application or one set of related applications, that are normally integrated with the hardware and delivered as a single system; thus, despite the large number of embedded computers, most users never really see that they are using a computer!

Figure 1.1 shows that during the last several years, the growth in cell phones that rely on embedded computers has been much faster than the growth rate of desktop computers. Note that the embedded computers are also found in digital TVs and set-top boxes, automobiles, digital cameras, music players, video games, and a variety of other such consumer devices, which further increases the gap between the number of embedded computers and desktop computers.

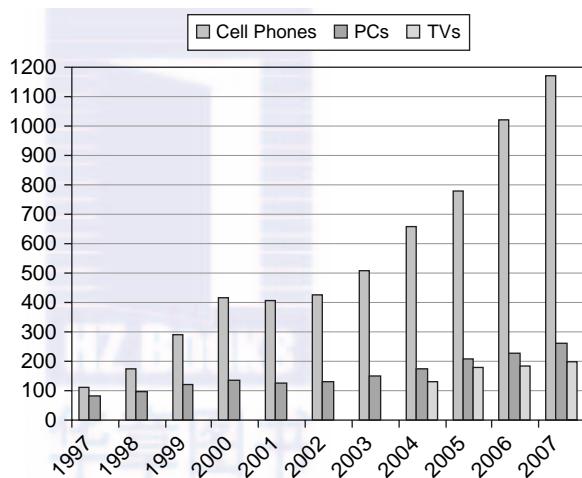


FIGURE 1.1 The number of cell phones, personal computers, and televisions manufactured per year between 1997 and 2007. (We have television data only from 2004.) More than a billion new cell phones were shipped in 2006. Cell phones sales exceeded PCs by only a factor of 1.4 in 1997, but the ratio grew to 4.5 in 2007. The total number in use in 2004 is estimated to be about 2.0B televisions, 1.8B cell phones, and 0.8B PCs. As the world population was about 6.4B in 2004, there were approximately one PC, 2.2 cell phones, and 2.5 televisions for every eight people on the planet. A 2006 survey of U.S. families found that they owned on average 12 gadgets, including three TVs, 2 PCs, and other devices such as game consoles, MP3 players, and cell phones.

Embedded applications often have unique application requirements that combine a minimum performance with stringent limitations on cost or power. For example, consider a music player: the processor need only be as fast as necessary to handle its limited function, and beyond that, minimizing cost and power are the most important objectives. Despite their low cost, embedded computers often have lower tolerance for failure, since the results can vary from upsetting (when your new television crashes) to devastating (such as might occur when the computer in a plane or cargo ship crashes). In consumer-oriented embedded applications, such as a digital home appliance, dependability is achieved primarily through simplicity—the emphasis is on doing one function as perfectly as possible. In large embedded systems, techniques of redundancy from the server world are often employed (see Section 6.9). Although this book focuses on general-purpose computers, most concepts apply directly, or with slight modifications, to embedded computers.

Elaboration: Elaborations are short sections used throughout the text to provide more detail on a particular subject that may be of interest. Disinterested readers may skip over an elaboration, since the subsequent material will never depend on the contents of the elaboration.

Many embedded processors are designed using *processor cores*, a version of a processor written in a hardware description language, such as Verilog or VHDL (see Chapter 4). The core allows a designer to integrate other application-specific hardware with the processor core for fabrication on a single chip.

What You Can Learn in This Book

Successful programmers have always been concerned about the performance of their programs, because getting results to the user quickly is critical in creating successful software. In the 1960s and 1970s, a primary constraint on computer performance was the size of the computer's memory. Thus, programmers often followed a simple credo: minimize memory space to make programs fast. In the last decade, advances in computer design and memory technology have greatly reduced the importance of small memory size in most applications other than those in embedded computing systems.

Programmers interested in performance now need to understand the issues that have replaced the simple memory model of the 1960s: the parallel nature of processors and the hierarchical nature of memories. Programmers who seek to build competitive versions of compilers, operating systems, databases, and even applications will therefore need to increase their knowledge of computer organization.

We are honored to have the opportunity to explain what's inside this revolutionary machine, unraveling the software below your program and the hardware under the covers of your computer. By the time you complete this book, we believe you will be able to answer the following questions:

- How are programs written in a high-level language, such as C or Java, translated into the language of the hardware, and how does the hardware execute the resulting program? Comprehending these concepts forms the basis of understanding the aspects of both the hardware and software that affect program performance.
- What is the interface between the software and the hardware, and how does software instruct the hardware to perform needed functions? These concepts are vital to understanding how to write many kinds of software.
- What determines the performance of a program, and how can a programmer improve the performance? As we will see, this depends on the original program, the software translation of that program into the computer's language, and the effectiveness of the hardware in executing the program.
- What techniques can be used by hardware designers to improve performance? This book will introduce the basic concepts of modern computer design. The interested reader will find much more material on this topic in our advanced book, *Computer Architecture: A Quantitative Approach*.
- What are the reasons for and the consequences of the recent switch from sequential processing to parallel processing? This book gives the motivation, describes the current hardware mechanisms to support parallelism, and surveys the new generation of “multicore” microprocessors (see Chapter 7).

Without understanding the answers to these questions, improving the performance of your program on a modern computer, or evaluating what features might make one computer better than another for a particular application, will be a complex process of trial and error, rather than a scientific procedure driven by insight and analysis.

This first chapter lays the foundation for the rest of the book. It introduces the basic ideas and definitions, places the major components of software and hardware in perspective, shows how to evaluate performance and power, introduces integrated circuits (the technology that fuels the computer revolution), and explains the shift to multicores.

In this chapter and later ones, you will likely see many new words, or words that you may have heard but are not sure what they mean. Don't panic! Yes, there is a lot of special terminology used in describing modern computers, but the terminology actually helps, since it enables us to describe precisely a function or capability. In addition, computer designers (including your authors) *love* using acronyms, which are *easy* to understand once you know what the letters stand for! To help you remember and locate terms, we have included a **highlighted** definition of every term in the margins the first time it appears in the text. After a short time of working with the terminology, you will be fluent, and your friends will be impressed as you correctly use acronyms such as BIOS, CPU, DIMM, DRAM, PCIE, SATA, and many others.

multicore
microprocessor A microprocessor containing multiple processors (“cores”) in a single integrated circuit.

acronym A word constructed by taking the initial letters of a string of words. For example: **RAM** is an acronym for Random AccessM emory, and **CPU** is an acronym for Central Processing Unit.

To reinforce how the software and hardware systems used to run a program will affect performance, we use a special section, *Understanding Program Performance*, throughout the book to summarize important insights into program performance. The first one appears below.

The performance of a program depends on a combination of the effectiveness of the algorithms used in the program, the software systems used to create and translate the program into machine instructions, and the effectiveness of the computer in executing those instructions, which may include input/output (I/O) operations. This table summarizes how the hardware and software affect performance.

Understanding Program Performance

Hardware or software component	How this component affects performance	Where is this topic covered?
Algorithm	Determines both the number of source-level statements and the number of I/O operations executed	Other books!
Programming language, compiler, and architecture	Determines the number of computer instructions for each source-level statement	Chapters 2 and 3
Processor and memory system	Determines how fast instructions can be executed	Chapters 4, 5, and 7
I/O system (hardware and operating system)	Determines how fast I/O operations may be executed	Chapter 6

Check Yourself sections are designed to help readers assess whether they comprehend the major concepts introduced in a chapter and understand the implications of those concepts. Some *Check Yourself* questions have simple answers; others are for discussion among a group. Answers to the specific questions can be found at the end of the chapter. *Check Yourself* questions appear only at the end of a section, making it easy to skip them if you are sure you understand the material.

Check Yourself

1. Section 1.1 showed that the number of embedded processors sold every year greatly outnumbers the number of desktop processors. Can you confirm or deny this insight based on your own experience? Try to count the number of embedded processors in your home. How does it compare with the number of desktop computers in your home?
2. As mentioned earlier, both the software and hardware affect the performance of a program. Can you think of examples where each of the following is the right place to look for a performance bottleneck?
 - The algorithm chosen
 - The programming language or compiler
 - The operating system
 - The processor
 - The I/O system and devices

In Paris they simply stared when I spoke to them in French; I never did succeed in making those idiots understand their own language.

Mark Twain, *The Innocents Abroad*, 1869

systems software

Software that provides services that are commonly useful, including operating systems, compilers, loaders, and assemblers.

operating system

Supervising program that manages the resources of a computer for the benefit of the programs that run on that computer.

1.2

Below Your Program

A typical application, such as a word processor or a large database system, may consist of millions of lines of code and rely on sophisticated software libraries that implement complex functions in support of the application. As we will see, the hardware in a computer can only execute extremely simple low-level instructions. To go from a complex application to the simple instructions involves several layers of software that interpret or translate high-level operations into simple computer instructions.

Figure 1.2 shows that these layers of software are organized primarily in a hierarchical fashion, with applications being the outermost ring and a variety of systems software sitting between the hardware and applications software.

There are many types of systems software, but two types of systems software are central to every computer system today: an operating system and a compiler. An **operating system** interfaces between a user's program and the hardware and provides a variety of services and supervisory functions. Among the most important functions are

- Handling basic input and output operations
- Allocating storage and memory
- Providing for protected sharing of the computer among multiple applications using it simultaneously.

Examples of operating systems in use today are Linux, MacOS, and Windows.

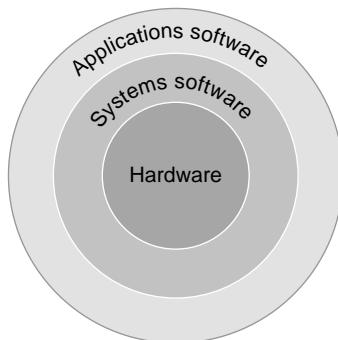


FIGURE 1.2 A simplified view of hardware and software as hierarchical layers, shown as concentric circles with hardware in the center and applications software outermost. In complex applications, there are often multiple layers of application software as well. For example, a database system may run on top of the systems software hosting an application, which in turn runs on top of the database.

Compilers perform another vital function: the translation of a program written in a high-level language, such as C, C++, Java, or Visual Basic into instructions that the hardware can execute. Given the sophistication of modern programming languages and the simplicity of the instructions executed by the hardware, the translation from a high-level language program to hardware instructions is complex. We give a brief overview of the process here and then go into more depth in Chapter 2 and Appendix B.

compiler A program that translates high-level language statements into assembly language statements.

From a High-Level Language to the Language of Hardware

To actually speak to electronic hardware, you need to send electrical signals. The easiest signals for computers to understand are *on* and *off*, and so the computer alphabet is just two letters. Just as the 26 letters of the English alphabet do not limit how much can be written, the two letters of the computer alphabet do not limit what computers can do. The two symbols for these two letters are the numbers 0 and 1, and we commonly think of the computer language as numbers in base 2, or *binary numbers*. We refer to each “letter” as a **binary digit** or **bit**. Computers are slaves to our commands, which are called **instructions**. Instructions, which are just collections of bits that the computer understands and obeys, can be thought of as numbers. For example, the bits

1000110010100000

binary digit Also called a **bit**. One of the two numbers in base 2 (0 or 1) that are the components of information.

tell one computer to add two numbers. Chapter 2 explains why we use numbers for instructions *and* data; we don’t want to steal that chapter’s thunder, but using numbers for both instructions and data is a foundation of computing.

instruction A command that computer hardware understands and obeys.

The first programmers communicated to computers in binary numbers, but this was so tedious that they quickly invented new notations that were closer to the way humans think. At first, these notations were translated to binary by hand, but this process was still tiresome. Using the computer to help program the computer, the pioneers invented programs to translate from symbolic notation to binary. The first of these programs was named an **assembler**. This program translates a symbolic version of an instruction into the binary version. For example, the programmer would write

add A,B

assembler A program that translates a symbolic version of instructions into the binary version.

and the assembler would translate this notation into

1000110010100000

This instruction tells the computer to add the two numbers A and B. The name coined for this symbolic language, still used today, is **assembly language**. In contrast, the binary language that the machine understands is the **machine language**.

assembly language A symbolic representation of machine instructions.

Although a tremendous improvement, assembly language is still far from the notations a scientist might like to use to simulate fluid flow or that an accountant might use to balance the books. Assembly language requires the programmer

machine language A binary representation of machine instructions.

to write one line for every instruction that the computer will follow, forcing the programmer to think like the computer.

The recognition that a program could be written to translate a more powerful language into computer instructions was one of the great breakthroughs in the early days of computing. Programmers today owe their productivity—and their sanity—to the creation of **high-level programming languages** and compilers that translate programs in such languages into instructions. Figure 1.3 shows the relationships among these programs and languages.

high-level programming language A portable language such as C, C++, Java, or Visual Basic that is composed of words and algebraic notation that can be translated by a compiler into assembly language.

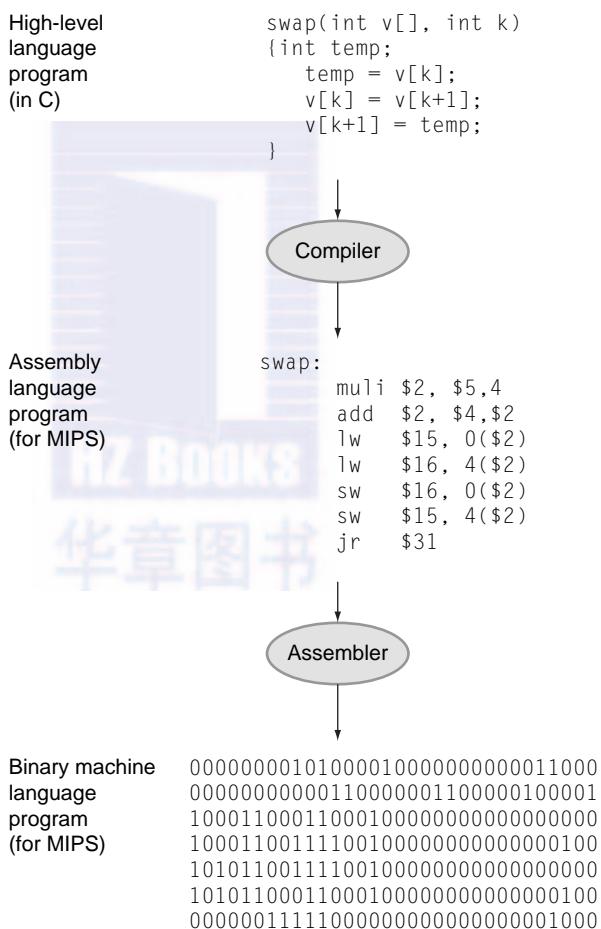


FIGURE 1.3 C program compiled into assembly language and then assembled into binary machine language. Although the translation from high-level language to binary machine language is shown in two steps, some compilers cut out the middleman and produce binary machine language directly. These languages and this program are examined in more detail in Chapter 2.

A compiler enables a programmer to write this high-level language expression:

A + B

The compiler would compile it into this assembly language statement:

add A,B

As shown above, the assembler would translate this statement into the binary instructions that tell the computer to add the two numbers A and B.

High-level programming languages offer several important benefits. First, they allow the programmer to think in a more natural language, using English words and algebraic notation, resulting in programs that look much more like text than like tables of cryptic symbols (see Figure 1.3). Moreover, they allow languages to be designed according to their intended use. Hence, Fortran was designed for scientific computation, Cobol for business data processing, Lisp for symbol manipulation, and so on. There are also domain-specific languages for even narrower groups of users, such as those interested in simulation of fluids, for example.

The second advantage of programming languages is improved programmer productivity. One of the few areas of widespread agreement in software development is that it takes less time to develop programs when they are written in languages that require fewer lines to express an idea. Conciseness is a clear advantage of high-level languages over assembly language.

The final advantage is that programming languages allow programs to be independent of the computer on which they were developed, since compilers and assemblers can translate high-level language programs to the binary instructions of any computer. These three advantages are so strong that today little programming is done in assembly language.

1.3

Under the Covers

Now that we have looked below your program to uncover the underlying software, let's open the covers of your computer to learn about the underlying hardware. The underlying hardware in any computer performs the same basic functions: inputting data, outputting data, processing data, and storing data. How these functions are performed is the primary topic of this book, and subsequent chapters deal with different parts of these four tasks.

When we come to an important point in this book, a point so important that we hope you will remember it forever, we emphasize it by identifying it as a *Big Picture* item. We have about a dozen Big Pictures in this book, the first being

The BIG Picture

the five components of a computer that perform the tasks of inputting, outputting, processing, and storing data.

The five classic components of a computer are input, output, memory, datapath, and control, with the last two sometimes combined and called the processor. Figure 1.4 shows the standard organization of a computer. This organization is independent of hardware technology: you can place every piece of every computer, past and present, into one of these five categories. To help you keep all this in perspective, the five components of a computer are shown on the front page of each of the following chapters, with the portion of interest to that chapter highlighted.

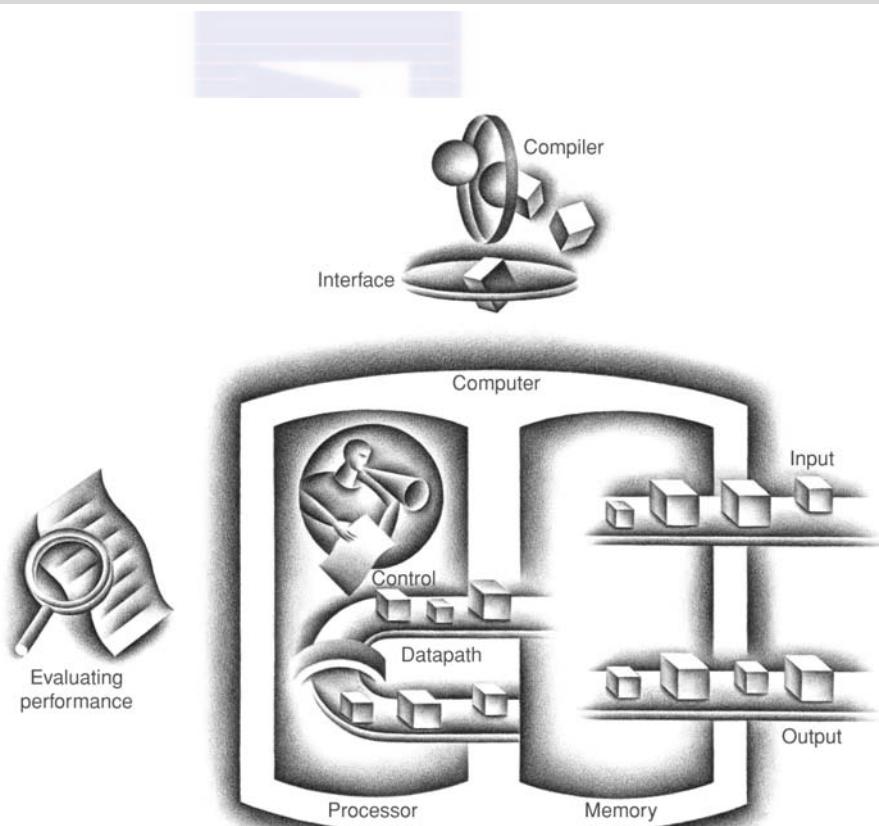


FIGURE 1.4 The organization of a computer, showing the five classic components. The processor gets instructions and data from memory. Input writes data to memory, and output reads data from memory. Control sends the signals that determine the operations of the datapath, memory, input, and output.



FIGURE 1.5 A desktop computer. The liquid crystal display (LCD) screen is the primary output device, and the keyboard and mouse are the primary input devices. On the right side is an Ethernet cable that connected the laptop to the network and the Web. The laptop contains the processor, memory, and additional I/O devices. This system is a Macbook Pro 15" laptop connected to an external display.

Figure 1.5 shows a computer with keyboard, wireless mouse, and screen. This photograph reveals two of the key components of computers: **input devices**, such as the keyboard and mouse, and **output devices**, such as the screen. As the names suggest, input feeds the computer, and output is the result of computation sent to the user. Some devices, such as networks and disks, provide both input and output to the computer.

Chapter 6 describes input/output (I/O) devices in more detail, but let's take an introductory tour through the computer hardware, starting with the external I/O devices.

input device

A mechanism through which the computer is fed information, such as the keyboard or mouse.

output device

A mechanism that conveys the result of a computation to a user or another computer.

I got the idea for the mouse while attending a talk at a computer conference. The speaker was so boring that I started daydreaming and hit upon the idea.

Doug Engelbart

Through computer displays I have landed an airplane on the deck of a moving carrier, observed a nuclear particle hit a potential well, flown in a rocket at nearly the speed of light and watched a computer reveal its innermost workings.

Ivan Sutherland, the “father” of computer graphics, *Scientific American*, 1984

liquid crystal display
A display technology using a thin layer of liquid polymers that can be used to transmit or block light according to whether a charge is applied.

active matrix display
A liquid crystal display using a transistor to control the transmission of light at each individual pixel.

pixel The smallest individual picture element. Screens are composed of hundreds of thousands to millions of pixels, organized in a matrix.

Anatomy of a Mouse

Although many users now take mice for granted, the idea of a pointing device such as a mouse was first shown by Doug Engelbart using a research prototype in 1967. The Alto, which was the inspiration for all workstations as well as for the Macintosh and Windows OS, included a mouse as its pointing device in 1973. By the 1990s, all desktop computers included this device, and new user interfaces based on graphics displays and mice became the norm.

The original mouse was electromechanical and used a large ball that when rolled across a surface would cause an *x* and *y* counter to be incremented. The amount of increase in each counter told how far the mouse had been moved.

The electromechanical mouse has largely been replaced by the newer all-optical mouse. The optical mouse is actually a miniature optical processor including an LED to provide lighting, a tiny black-and-white camera, and a simple optical processor. The LED illuminates the surface underneath the mouse; the camera takes 1500 sample pictures a second under the illumination. Successive pictures are sent to a simple optical processor that compares the images and determines whether the mouse has moved and how far. The replacement of the electromechanical mouse by the electro-optical mouse is an illustration of a common phenomenon where the decreasing costs and higher reliability of electronics cause an electronic solution to replace the older electromechanical technology. On page 22 we'll see another example: flash memory.

Through the Looking Glass

The most fascinating I/O device is probably the graphics display. All laptop and handheld computers, calculators, cellular phones, and almost all desktop computers now use **liquid crystal displays (LCDs)** to get a thin, low-power display. The LCD is not the source of light; instead, it controls the transmission of light. A typical LCD includes rod-shaped molecules in a liquid that form a twisting helix that bends light entering the display, from either a light source behind the display or less often from reflected light. The rods straighten out when a current is applied and no longer bend the light. Since the liquid crystal material is between two screens polarized at 90 degrees, the light cannot pass through unless it is bent. Today, most LCD displays use an **active matrix** that has a tiny transistor switch at each pixel to precisely control current and make sharper images. A red-green-blue mask associated with each dot on the display determines the intensity of the three color components in the final image; in a color active matrix LCD, there are three transistor switches at each point.

The image is composed of a matrix of picture elements, or **pixels**, which can be represented as a matrix of bits, called a *bit map*. Depending on the size of the screen and the resolution, the display matrix ranges in size from 640×480 to 2560×1600 pixels in 2008. A color display might use 8 bits for each of the three colors (red, blue, and green), for 24 bits per pixel, permitting millions of different colors to be displayed.

The computer hardware support for graphics consists mainly of a *raster refresh buffer*, or *frame buffer*, to store the bit map. The image to be represented onscreen is stored in the frame buffer, and the bit pattern per pixel is read out to the graphics display at the refresh rate. Figure 1.6 shows a frame buffer with a simplified design of just 4 bits per pixel.

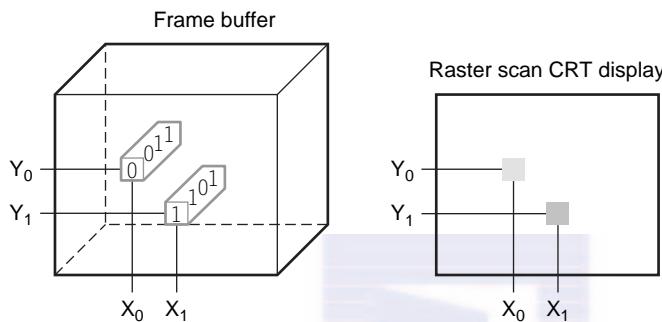


FIGURE 1.6 Each coordinate in the frame buffer on the left determines the shade of the corresponding coordinate for the raster scan CRT display on the right. Pixel (X_0, Y_0) contains the bit pattern 0011, which is a lighter shade on the screen than the bit pattern 1101 in pixel (X_1, Y_1) .

The goal of the bit map is to faithfully represent what is on the screen. The challenges in graphics systems arise because the human eye is very good at detecting even subtle changes on the screen.

Opening the Box

If we open the box containing the computer, we see a fascinating board of thin plastic, covered with dozens of small gray or black rectangles. Figure 1.7 shows the contents of the laptop computer in Figure 1.5. The **motherboard** is shown in the upper part of the photo. Two disk drives are in front—the hard drive on the left and a DVD drive on the right. The hole in the middle is for the laptop battery.

The small rectangles on the motherboard contain the devices that drive our advancing technology, called **integrated circuits** and nicknamed **chips**. The board is composed of three pieces: the piece connecting to the I/O devices mentioned earlier, the **memory**, and the **processor**.

The **memory** is where the programs are kept when they are running; it also contains the data needed by the running programs. Figure 1.8 shows that memory is found on the two small boards, and each small memory board contains eight integrated circuits. The memory in Figure 1.8 is built from DRAM chips. **DRAM**

motherboard

A plastic board containing packages of integrated circuits or chips, including processor, cache, memory, and connectors for I/O devices such as networks and disks.

integrated circuit

Also called a **chip**. A device combining dozens to millions of transistors.

memory

The storage area in which programs are kept when they are running and that contains the data needed by the running programs.

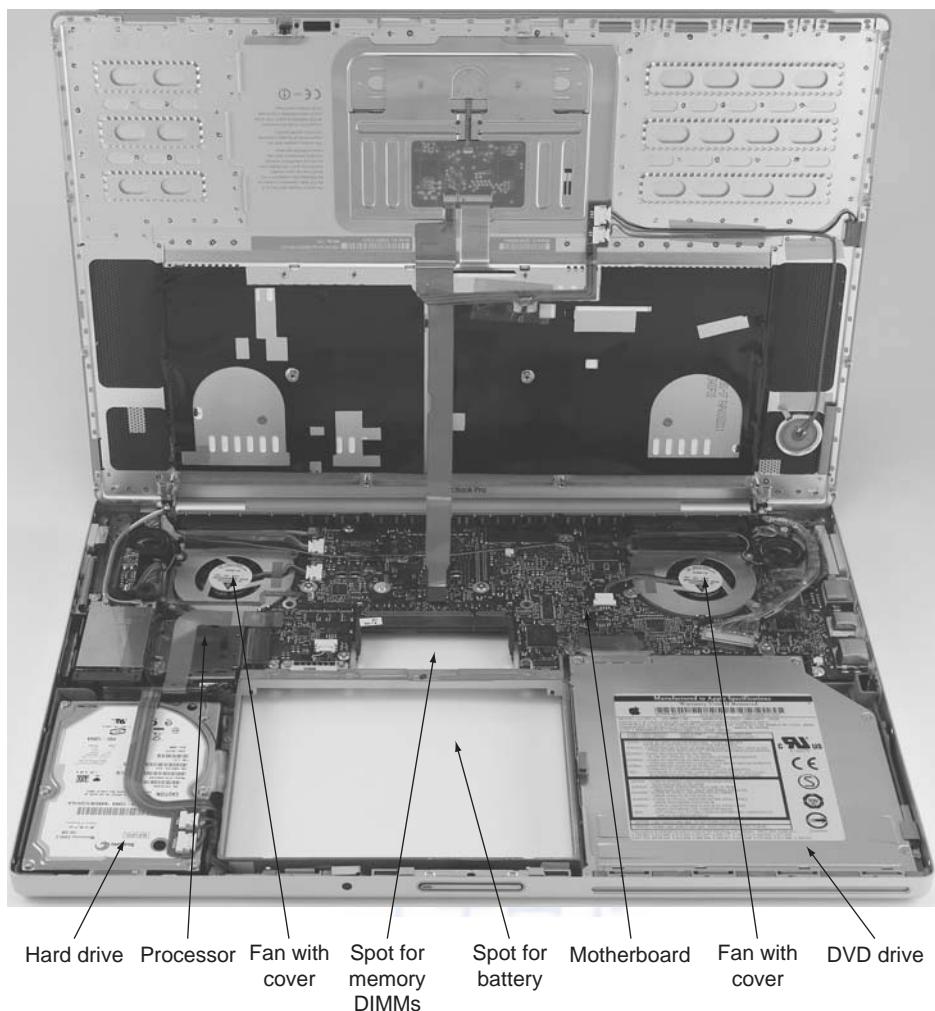


FIGURE 1.7 Inside the laptop computer of Figure 1.5. The shiny box with the white label on the lower left is a 100 GB SATA hard disk drive, and the shiny metal box on the lower right side is the DVD drive. The hole between them is where the laptop battery would be located. The small hole above the battery hole is for memory DIMMs. Figure 1.8 is a close-up of the DIMMs, which are inserted from the bottom in this laptop. Above the battery hole and DVD drive is a printed circuit board (PC board), called the *motherboard*, which contains most of the electronics of the computer. The two shiny circles in the upper half of the picture are two fans with covers. The processor is the large raised rectangle just below the left fan. Photo courtesy of OtherWorldComputing.com.

stands for **dynamic random access memory**. Several DRAMs are used together to contain the instructions and data of a program. In contrast to sequential access memories, such as magnetic tapes, the *RAM* portion of the term DRAM means that memory accesses take basically the same amount of time no matter what portion of the memory is read.

dynamic random access memory (DRAM)
Memory built as an integrated circuit; it provides random access to any location.

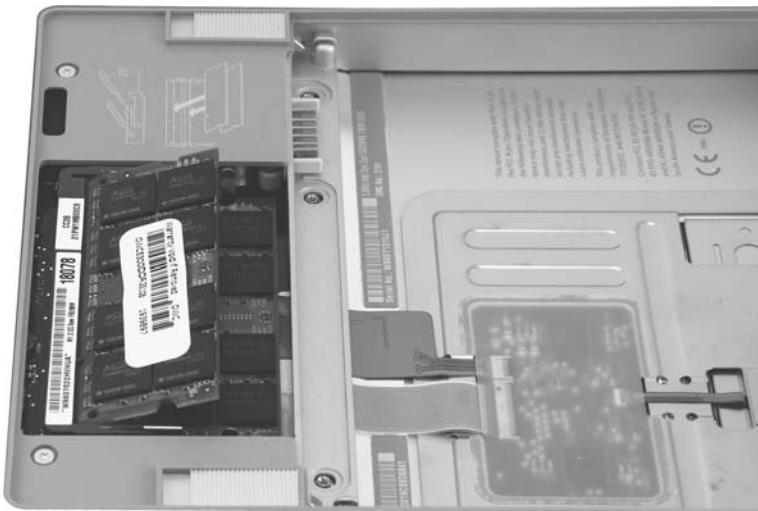


FIGURE 1.8 Close-up of the bottom of the laptop reveals the memory. The main memory is contained on one or more small boards shown on the left. The hole for the battery is to the right. The DRAM chips are mounted on these boards (called **DIMMs**, for dual inline memory modules) and then plugged into the connectors. Photo courtesy of OtherWorldComputing.com.

The **processor** is the active part of the board, following the instructions of a program to the letter. It adds numbers, tests numbers, signals I/O devices to activate, and so on. The processor is under the fan and covered by a heat sink on the left side of Figure 1.7. Occasionally, people call the processor the **CPU**, for the more bureaucratic-sounding **central processor unit**.

Descending even lower into the hardware, Figure 1.9 reveals details of a microprocessor. The processor logically comprises two main components: datapath and control, the respective brawn and brain of the processor. The **datapath** performs the arithmetic operations, and **control** tells the datapath, memory, and I/O devices what to do according to the wishes of the instructions of the program. Chapter 4 explains the datapath and control for a higher-performance design.

dual inline memory module (DIMM)
A small board that contains DRAM chips on both sides. (SIMMs have DRAMs on only one side.)

central processor unit (CPU) Also called **processor**. The active part of the computer, which contains the datapath and control and which adds numbers, tests numbers, signals I/O devices to activate, and so on.

datapath The component of the processor that performs arithmetic operations

control The component of the processor that commands the datapath, memory, and I/O devices according to the instructions of the program.

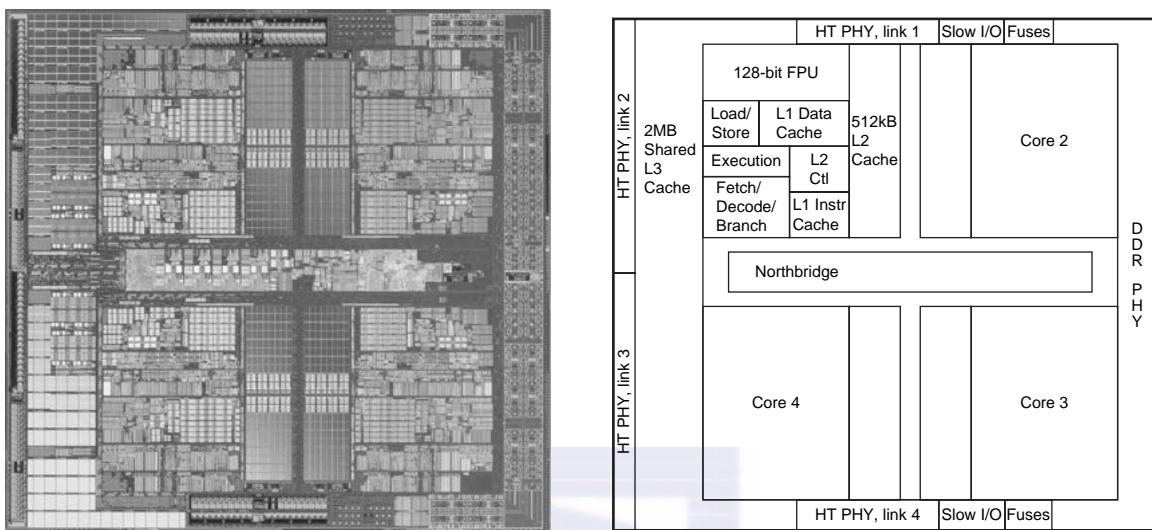


FIGURE 1.9 Inside the AMD Barcelona microprocessor. The left-hand side is a microphotograph of the AMD Barcelona processor chip, and the right-hand side shows the major blocks in the processor. This chip has four processors or “cores”. The microprocessor in the laptop in Figure 1.7 has two cores per chip, called an Intel Core 2 Duo.

cache memory A small, fast memory that acts as a buffer for a slower, larger memory.

static random access memory(SRAM) Also memory built as an integrated circuit, but faster and less dense than DRAM.

abstraction A model that renders lower-level details of computer systems temporarily invisible to facilitate design of sophisticated systems.

Descending into the depths of any component of the hardware reveals insights into the computer. Inside the processor is another type of memory—cache memory. **Cache memory** consists of a small, fast memory that acts as a buffer for the DRAM memory. (The nontechnical definition of *cache* is a safe place for hiding things.) Cache is built using a different memory technology, **static random access memory (SRAM)**. SRAM is faster but less dense, and hence more expensive, than DRAM (see Chapter 5).

You may have noticed a common theme in both the software and the hardware descriptions: delving into the depths of hardware or software reveals more information or, conversely, lower-level details are hidden to offer a simpler model at higher levels. The use of such layers, or **abstractions**, is a principal technique for designing very sophisticated computer systems.

One of the most important abstractions is the interface between the hardware and the lowest-level software. Because of its importance, it is given a special

name: the **instruction set architecture**, or simply **architecture**, of a computer. The instruction set architecture includes anything programmers need to know to make a binary machine language program work correctly, including instructions, I/O devices, and so on. Typically, the operating system will encapsulate the details of doing I/O, allocating memory, and other low-level system functions so that application programmers do not need to worry about such details. The combination of the basic instruction set and the operating system interface provided for application programmers is called the **application binary interface (ABI)**.

An instruction set architecture allows computer designers to talk about functions independently from the hardware that performs them. For example, we can talk about the functions of a digital clock (keeping time, displaying the time, setting the alarm) independently from the clock hardware (quartz crystal, LED displays, plastic buttons). Computer designers distinguish architecture from an **implementation** of an architecture along the same lines: an implementation is hardware that obeys the architecture abstraction. These ideas bring us to another Big Picture.

instruction set architecture Also called **architecture**. An abstract interface between the hardware and the lowest-level software that encompasses all the information necessary to write a machine language program that will run correctly, including instructions, registers, memory access, I/O,

application binary interface (ABI) The user portion of the instruction set plus the operating system interfaces used by application programmers. Defines a standard for binary portability across computers.

implementation Hardware that obeys the architecture abstraction.

The BIG Picture

volatile memory Storage, such as DRAM, that retains data only if it is receiving power.

nonvolatile memory A form of memory that retains data even in the absence of a power source and that is used to store programs between runs. Magnetic disk is nonvolatile.

main memory Also called **primary memory**. Memory used to hold programs while they are running; typically consists of DRAM in today's computers.

Both hardware and software consist of hierarchical layers, with each lower layer hiding details from the level above. This principle of *abstraction* is the way both hardware designers and software designers cope with the complexity of computer systems. One key interface between the levels of abstraction is the *instruction set architecture*—the interface between the hardware and low-level software. This abstract interface enables many *implementations* of varying cost and performance to run identical software.

A Safe Place for Data

Thus far, we have seen how to input data, compute using the data, and display data. If we were to lose power to the computer, however, everything would be lost because the memory inside the computer is **volatile**—that is, when it loses power, it forgets. In contrast, a DVD doesn't forget the recorded film when you turn off the power to the DVD player and is thus a **nonvolatile memory** technology.

To distinguish between the volatile memory used to hold data and programs while they are running and this nonvolatile memory used to store data and programs between runs, the term **main memory** or **primary memory** is used for the

secondary memory

Nonvolatile emory used to store programs and data between runs; typically consists of magnetic disks in today's computers.

magnetic disk Also called **hard disk**. A form of nonvolatile secondary memory composed of rotating platters coated with a magnetic recording material.

flash memory

A nonvolatile semiconductor memory. It is cheaper and slower than DRAM but more expensive and faster than magnetic disks.

former, and **secondary memory** for the latter. DRAMs have dominated main memory since 1975, but **magnetic disks** have dominated secondary memory since 1965. The primary nonvolatile storage used in all server computers and workstations is the **magnetic hard disk**. **Flash memory**, a nonvolatile semiconductor memory, is used instead of disks in mobile devices such as cell phones and is increasingly replacing disks in music players and even laptops.

As Figure 1.10 shows, a magnetic hard disk consists of a collection of platters, which rotate on a spindle at 5400 to 15,000 revolutions per minute. The metal platters are covered with magnetic recording material on both sides, similar to the material found on a cassette or videotape. To read and write information on a hard disk, a movable *arm* containing a small electromagnetic coil called a *read-write head* is located just above each surface. The entire drive is permanently sealed to control the environment inside the drive, which, in turn, allows the disk heads to be much closer to the drive surface.

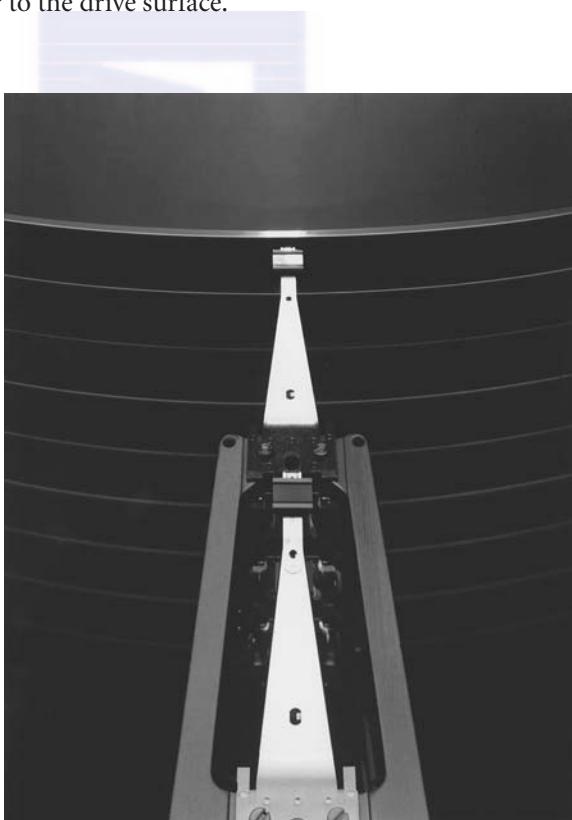


FIGURE 1.10 A disk showing 10 disk platters and the read/write heads.

Diameters of hard disks vary by more than a factor of 3 today, from 1 inch to 3.5 inches, and have been shrunk over the years to fit into new products; workstation servers, personal computers, laptops, palmtops, and digital cameras have all inspired new disk form factors. Traditionally, the widest disks have the highest performance and the smallest disks have the lowest unit cost. The best cost per **gigabyte** varies. Although most hard drives appear inside computers, as in Figure 1.7, hard drives can also be attached using external interfaces such as universal serial bus (USB).

The use of mechanical components means that access times for magnetic disks are much slower than for DRAMs: disks typically take 5–20 milliseconds, while DRAMs take 50–70 nanoseconds—making DRAMs about 100,000 times faster. Yet disks have much lower costs than DRAM for the same storage capacity, because the production costs for a given amount of disk storage are lower than for the same amount of integrated circuit. In 2008, the cost per gigabyte of disk is 30 to 100 times less expensive than DRAM.

Thus, there are three primary differences between magnetic disks and main memory: disks are nonvolatile because they are magnetic; they have a slower access time because they are mechanical devices; and they are cheaper per gigabyte because they have very high storage capacity at a modest cost.

Many have tried to invent a technology cheaper than DRAM but faster than disk to fill that gap, but many have failed. Challengers have never had a product to market at the right time. By the time a new product would ship, DRAMs and disks had continued to make rapid advances, costs had dropped accordingly, and the challenging product was immediately obsolete.

Flash memory, however, is a serious challenger. This semiconductor memory is nonvolatile like disks and has about the same bandwidth, but latency is 100 to 1000 times faster than disk. Flash is popular in cameras and portable music players because it comes in much smaller capacities, it is more rugged, and it is more power efficient than disks, despite the cost per gigabyte in 2008 being about 6 to 10 times higher than disk. Unlike disks and DRAM, flash memory bits wear out after 100,000 to 1,000,000 writes. Thus, file systems must keep track of the number of writes and have a strategy to avoid wearing out storage, such as by moving popular data. Chapter 6 describes flash in more detail.

Although hard drives are not removable, there are several storage technologies in use that include the following:

- Optical disks, including both compact disks (CDs) and digital video disks (DVDs), constitute the most common form of removable storage. The Blu-Ray (BD) optical disk standard is the heir-apparent to DVD.
- Flash-based removable memory cards typically attach to a USB connection and are often used to transfer files.
- Magnetic tape provides only slow serial access and has been used to back up disks, a role now often replaced by duplicate hard drives.

gigabyte Traditionally 1,073,741,824 (2^{30}) bytes, although some communications and secondary storage systems have redefined it to mean 1,000,000,000 (10^9) bytes. Similarly, depending on the context, megabyte is either 2^{20} or 10^6 bytes.

Optical disk technology works differently than magnetic disk technology. In a CD, data is recorded in a spiral fashion, with individual bits being recorded by burning small pits—approximately 1 micron (10^{-6} meters) in diameter—into the disk surface. The disk is read by shining a laser at the CD surface and determining by examining the reflected light whether there is a pit or flat (reflective) surface. DVDs use the same approach of bouncing a laser beam off a series of pits and flat surfaces. In addition, there are multiple layers that the laser beam can focus on, and the size of each bit is much smaller, which together increase capacity significantly. Blu-Ray uses shorter wavelength lasers that shrink the size of the bits and thereby increase capacity.

Optical disk writers in personal computers use a laser to make the pits in the recording layer on the CD or DVD surface. This writing process is relatively slow, taking from minutes (for a full CD) to tens of minutes (for a full DVD). Thus, for large quantities a different technique called *pressing* is used, which costs only pennies per optical disk.

Rewritable CDs and DVDs use a different recording surface that has a crystalline, reflective material; pits are formed that are not reflective in a manner similar to that for a write-once CD or DVD. To erase the CD or DVD, the surface is heated and cooled slowly, allowing an annealing process to restore the surface recording layer to its crystalline structure. These rewritable disks are the most expensive, with write-once being cheaper; for read-only disks—used to distribute software, music, or movies—both the disk cost and recording cost are much lower.

Communicating with Other Computers

We've explained how we can input, compute, display, and save data, but there is still one missing item found in today's computers: computer networks. Just as the processor shown in Figure 1.4 is connected to memory and I/O devices, networks interconnect whole computers, allowing computer users to extend the power of computing by including communication. Networks have become so popular that they are the backbone of current computer systems; a new computer without an optional network interface would be ridiculed. Networked computers have several major advantages:

- *Communication:* Information is exchanged between computers at high speeds.
- *Resource sharing:* Rather than each computer having its own I/O devices, devices can be shared by computers on the network.
- *Nonlocal access:* By connecting computers over long distances, users need not be near the computer they are using.

Networks vary in length and performance, with the cost of communication increasing according to both the speed of communication and the distance that information travels. Perhaps the most popular type of network is *Ethernet*. It can be up to a kilometer long and transfer at up to 10 gigabits per second. Its length and

speed make Ethernet useful to connect computers on the same floor of a building; hence, it is an example of what is generically called a **local area network**. Local area networks are interconnected with switches that can also provide routing services and security. **Wide area networks** cross continents and are the backbone of the Internet, which supports the World Wide Web. They are typically based on optical fibers and are leased from telecommunication companies.

Networks have changed the face of computing in the last 25 years, both by becoming much more ubiquitous and by making dramatic increases in performance. In the 1970s, very few individuals had access to electronic mail, the Internet and Web did not exist, and physically mailing magnetic tapes was the primary way to transfer large amounts of data between two locations. Local area networks were almost nonexistent, and the few existing wide area networks had limited capacity and restricted access.

As networking technology improved, it became much cheaper and had a much higher capacity. For example, the first standardized local area network technology, developed about 25 years ago, was a version of Ethernet that had a maximum capacity (also called bandwidth) of 10 million bits per second, typically shared by tens of, if not a hundred, computers. Today, local area network technology offers a capacity of from 100 million bits per second to 10 gigabits per second, usually shared by at most a few computers. Optical communications technology has allowed similar growth in the capacity of wide area networks, from hundreds of kilobits to gigabits and from hundreds of computers connected to a worldwide network to millions of computers connected. This combination of dramatic rise in deployment of networking combined with increases in capacity have made network technology central to the information revolution of the last 25 years.

For the last decade another innovation in networking is reshaping the way computers communicate. Wireless technology is widespread, and laptops now incorporate this technology. The ability to make a radio in the same low-cost semiconductor technology (CMOS) used for memory and microprocessors enabled a significant improvement in price, leading to an explosion in deployment. Currently available wireless technologies, called by the IEEE standard name 802.11, allow for transmission rates from 1 to nearly 100 million bits per second. Wireless technology is quite a bit different from wire-based networks, since all users in an immediate area share the airwaves.

- Semiconductor DRAM and disk storage differ significantly. Describe the fundamental difference for each of the following: volatility, access time, and cost.

local area network (LAN) A network designed to carry data within a geographically confined area, typically within a single building.

wide area network (WAN) A network extended over hundreds of kilometers that can span a continent.

Check Yourself

Technologies for Building Processors and Memory

Processors and memory have improved at an incredible rate, because computer designers have long embraced the latest in electronic technology to try to win the race to design a better computer. Figure 1.11 shows the technologies that have been

used over time, with an estimate of the relative performance per unit cost for each technology. Section 1.7 explores the technology that has fueled the computer industry since 1975 and will continue to do so for the foreseeable future. Since this technology shapes what computers will be able to do and how quickly they will evolve, we believe all computer professionals should be familiar with the basics of integrated circuits.

Year	Technology used in computers	Relative performance/unit cost
1951	Vacuum tube	1
1965	Transistor	35
1975	Integrated circuit	900
1995	Very large-scale integrated circuit	2,400,000
2005	Ultra large-scale integrated circuit	6,200,000,000

FIGURE 1.11 Relative performance per unit cost of technologies used in computers over time. Source: Computer Museum, Boston, with 2005 extrapolated by the authors. See Section 1.10 on the CD.

vacuum tube An electronic component, predecessor of the transistor, that consists of a hollow glass tube about 5 to 10 cm long from which as much air has been removed as possible and that uses an electron beam to transfer data.

transistor An on/off switch controlled by an electric signal.

very large-scale integrated (VLSI) circuit A device containing hundreds of thousands to millions of transistors.

A **transistor** is simply an on/off switch controlled by electricity. The *integrated circuit* (IC) combined dozens to hundreds of transistors into a single chip. To describe the tremendous increase in the number of transistors from hundreds to millions, the adjective *very large scale* is added to the term, creating the abbreviation **VLSI**, for **very large-scale integrated circuit**.

This rate of increasing integration has been remarkably stable. Figure 1.12 shows the growth in DRAM capacity since 1977. For 20 years, the industry has consistently quadrupled capacity every 3 years, resulting in an increase in excess of 16,000 times! This increase in transistor count for an integrated circuit is popularly known as **Moore's law**, which states that transistor capacity doubles every 18–24 months. Moore's law resulted from a prediction of such growth in IC capacity made by Gordon Moore, one of the founders of Intel during the 1960s.

Sustaining this rate of progress for almost 40 years has required incredible innovation in manufacturing techniques. In Section 1.7, we discuss how to manufacture integrated circuits.

1.4

Performance

Assessing the performance of computers can be quite challenging. The scale and intricacy of modern software systems, together with the wide range of performance improvement techniques employed by hardware designers, have made performance assessment much more difficult.

When trying to choose among different computers, performance is an important attribute. Accurately measuring and comparing different computers is critical to

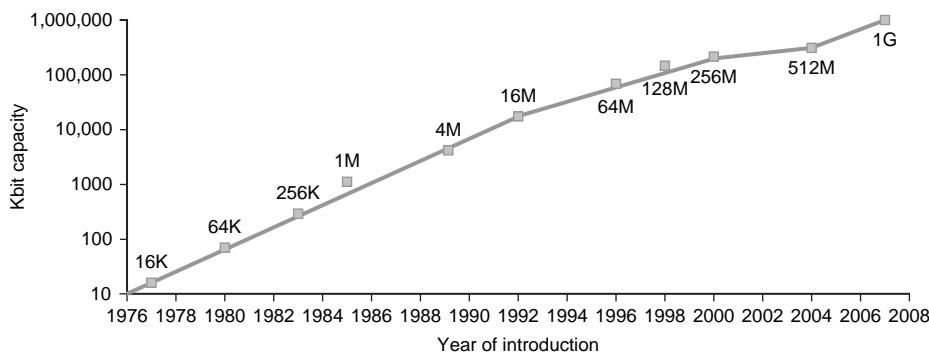


FIGURE 1.12 Growth of capacity per DRAM chip over time. The *y*-axis is measured in Kilobits, where $K = 1024 (2^{10})$. The DRAM industry quadrupled capacity almost every three years, a 60% increase per year, for 20 years. In recent years, the rate has slowed down and is somewhat closer to doubling every two years to three years.

purchasers and therefore to designers. The people selling computers know this as well. Often, salespeople would like you to see their computer in the best possible light, whether or not this light accurately reflects the needs of the purchaser's application. Hence, understanding how best to measure performance and the limitations of performance measurements is important in selecting a computer.

The rest of this section describes different ways in which performance can be determined; then, we describe the metrics for measuring performance from the viewpoint of both a computer user and a designer. We also look at how these metrics are related and present the classical processor performance equation, which we will use throughout the text.

Defining Performance

When we say one computer has better performance than another, what do we mean? Although this question might seem simple, an analogy with passenger airplanes shows how subtle the question of performance can be. Figure 1.13 shows some typical passenger airplanes, together with their cruising speed, range, and capacity. If we wanted to know which of the planes in this table had the best performance, we would first need to define performance. For example, considering different measures of performance, we see that the plane with the highest cruising speed is the Concorde, the plane with the longest range is the DC-8, and the plane with the largest capacity is the 747.

Let's suppose we define performance in terms of speed. This still leaves two possible definitions. You could define the fastest plane as the one with the highest cruising speed, taking a single passenger from one point to another in the least time. If you

Airplane	Passenger capacity	Cruising range (miles)	Cruising speed (m.p.h.)	Passenger throughput (passengers × m.p.h.)
Boeing 777	375	4630	610	228,750
Boeing 747	470	4150	610	286,700
BAC/Sud Concorde	132	4000	1350	178,200
Douglas DC-8-50	146	8720	544	79,424

FIGURE 1.13 The capacity, range, and speed for a number of commercial airplanes. The last column shows the rate at which the airplane transports passengers, which is the capacity times the cruising speed (ignoring range and takeoff and landing times).

response time Also called **execution time**. The total time required for the computer to complete a task, including disk accesses, memory accesses, I/O activities, operating system overhead, CPU execution time, and so on.

throughput Also called **bandwidth**. Another measure of performance, it is the number of tasks completed per unit time.

were interested in transporting 450 passengers from one point to another, however, the 747 would clearly be the fastest, as the last column of the figure shows. Similarly, we can define computer performance in several different ways.

If you were running a program on two different desktop computers, you'd say that the faster one is the desktop computer that gets the job done first. If you were running a datacenter that had several servers running jobs submitted by many users, you'd say that the faster computer was the one that completed the most jobs during a day. As an individual computer user, you are interested in reducing **response time**—the time between the start and completion of a task—also referred to as **execution time**. Datacenter managers are often interested in increasing **throughput** or **bandwidth**—the total amount of work done in a given time. Hence, in most cases, we will need different performance metrics as well as different sets of applications to benchmark embedded and desktop computers, which are more focused on response time, versus servers, which are more focused on throughput.

EXAMPLE

Throughput and Response Time

Do the following changes to a computer system increase throughput, decrease response time, or both?

- Replacing the processor in a computer with a faster version
- Adding additional processors to a system that uses multiple processors for separate tasks—for example, searching the World Wide Web

ANSWER

Decreasing response time almost always improves throughput. Hence, in case 1, both response time and throughput are improved. In case 2, no one task gets work done faster, so only throughput increases.

If, however, the demand for processing in the second case was almost as large as the throughput, the system might force requests to queue up. In this case, increasing the throughput could also improve response time, since it would reduce the waiting time in the queue. Thus, in many real computer systems, changing either execution time or throughput often affects the other.

In discussing the performance of computers, we will be primarily concerned with response time for the first few chapters. To maximize performance, we want to minimize response time or execution time for some task. Thus, we can relate performance and execution time for a computer X:

$$\text{Performance}_X = \frac{1}{\text{Execution time}_X}$$

This means that for two computers X and Y, if the performance of X is greater than the performance of Y, we have

$$\begin{aligned} \text{Performance}_X &> \text{Performance}_Y \\ \frac{1}{\text{Execution time}_X} &> \frac{1}{\text{Execution time}_Y} \\ \text{Execution time}_Y &> \text{Execution time}_X \end{aligned}$$

That is, the execution time on Y is longer than that on X, if X is faster than Y.

In discussing a computer design, we often want to relate the performance of two different computers quantitatively. We will use the phrase “X is n times faster than Y”—or equivalently “X is n times as fast as Y”—to mean

$$\frac{\text{Performance}_X}{\text{Performance}_Y} = n$$

If X is n times faster than Y, then the execution time on Y is n times longer than it is on X:

$$\frac{\text{Performance}_X}{\text{Performance}_Y} = \frac{\text{Execution time}_Y}{\text{Execution time}_X} = n$$

Relative Performance

If computer A runs a program in 10 seconds and computer B runs the same program in 15 seconds, how much faster is A than B?

EXAMPLE

We know that A is n times faster than B if

$$\frac{\text{Performance}_A}{\text{Performance}_B} = \frac{\text{Execution time}_B}{\text{Execution time}_A} = n$$

ANSWER

Thus the performance ratio is

$$\frac{15}{10} = 1.5$$

and A is therefore 1.5 times faster than B.

In the above example, we could also say that computer B is 1.5 times *slower than* computer A, since

$$\frac{\text{Performance}_A}{\text{Performance}_B} = 1.5$$

means that

$$\frac{\text{Performance}_A}{1.5} = \text{Performance}_B$$

For simplicity, we will normally use the terminology *faster than* when we try to compare computers quantitatively. Because performance and execution time are reciprocals, increasing performance requires decreasing execution time. To avoid the potential confusion between the terms *increasing* and *decreasing*, we usually say “improve performance” or “improve execution time” when we mean “increase performance” and “decrease execution time.”

Measuring Performance

Time is the measure of computer performance: the computer that performs the same amount of work in the least time is the fastest. Program *execution time* is measured in seconds per program. However, time can be defined in different ways, depending on what we count. The most straightforward definition of time is called *wall clock time*, *response time*, or *elapsed time*. These terms mean the total time to complete a task, including disk accesses, memory accesses, input/output (I/O) activities, operating system overhead—everything.

Computers are often shared, however, and a processor may work on several programs simultaneously. In such cases, the system may try to optimize throughput rather than attempt to minimize the elapsed time for one program. Hence, we often want to distinguish between the elapsed time and the time that the processor is working on our behalf. *CPU execution time* or simply *CPU time*, which recognizes this distinction, is the time the CPU spends computing for this task and does not include time spent waiting for I/O or running other programs. (Remember, though, that the response time experienced by the user will be the elapsed time of the program, not the CPU time.) CPU time can be further divided into the CPU time spent in the program, called *user CPU time*, and the CPU time spent in the operating system performing tasks on behalf of the program, called *system CPU time*. Differentiating between system and user CPU time is difficult to

CPU execution time
Also called **CPU time**.
The actual time the CPU spends computing for a specific task.

user CPU time The CPU time spent in a program itself.

system CPU time
The CPU time spent in the operating system performing tasks on behalf of the program.

do accurately, because it is often hard to assign responsibility for operating system activities to one user program rather than another and because of the functionality differences among operating systems.

For consistency, we maintain a distinction between performance based on elapsed time and that based on CPU execution time. We will use the term *system performance* to refer to elapsed time on an unloaded system and *CPU performance* to refer to user CPU time. We will focus on CPU performance in this chapter, although our discussions of how to summarize performance can be applied to either elapsed time or CPU time measurements.

Different applications are sensitive to different aspects of the performance of a computer system. Many applications, especially those running on servers, depend as much on I/O performance, which, in turn, relies on both hardware and software. Total elapsed time measured by a wall clock is the measurement of interest. In some application environments, the user may care about throughput, response time, or a complex combination of the two (e.g., maximum throughput with a worst-case response time). To improve the performance of a program, one must have a clear definition of what performance metric matters and then proceed to look for performance bottlenecks by measuring program execution and looking for the likely bottlenecks. In the following chapters, we will describe how to search for bottlenecks and improve performance in various parts of the system.

Although as computer users we care about time, when we examine the details of a computer it's convenient to think about performance in other metrics. In particular, computer designers may want to think about a computer by using a measure that relates to how fast the hardware can perform basic functions. Almost all computers are constructed using a clock that determines when events take place in the hardware. These discrete time intervals are called *clock cycles* (or *ticks*, *clock ticks*, *clock periods*, *clocks*, *cycles*). Designers refer to the length of a *clock period* both as the time for a complete *clock cycle* (e.g., 250 picoseconds, or 250 ps) and as the *clock rate* (e.g., 4 gigahertz, or 4 GHz), which is the inverse of the clock period. In the next subsection, we will formalize the relationship between the clock cycles of the hardware designer and the seconds of the computer user.

1. Suppose we know that an application that uses both a desktop client and a remote server is limited by network performance. For the following changes, state whether only the throughput improves, both response time and throughput improve, or neither improves.
 - a. An extra network channel is added between the client and the server, increasing the total network throughput and reducing the delay to obtain network access (since there are now two channels).

Understanding Program Performance

clock cycle Also called *tick*, *clock tick*, *clock period*, *clock*, *cycle*. The time for one clock period, usually of the processor clock, which runs at a constant rate.

clock period The length of each clock cycle.

Check Yourself

- b. The networking software is improved, thereby reducing the network communication delay, but not increasing throughput.
 - c. More memory is added to the computer.
2. Computer C's performance is 4 times faster than the performance of computer B, which runs a given application in 28 seconds. How long will computer C take to run that application?

CPU Performance and Its Factors

Users and designers often examine performance using different metrics. If we could relate these different metrics, we could determine the effect of a design change on the performance as experienced by the user. Since we are confining ourselves to CPU performance at this point, the bottom-line performance measure is CPU execution time. A simple formula relates the most basic metrics (clock cycles and clock cycle time) to CPU time:

$$\text{CPU execution time} = \frac{\text{CPU clock cycles for a program}}{\text{Clock cycle time}}$$

Alternatively, because clock rate and clock cycle time are inverses,

$$\text{CPU execution time} = \frac{\text{CPU clock cycles for a program}}{\text{Clock rate}}$$

This formula makes it clear that the hardware designer can improve performance by reducing the number of clock cycles required for a program or the length of the clock cycle. As we will see in later chapters, the designer often faces a trade-off between the number of clock cycles needed for a program and the length of each cycle. Many techniques that decrease the number of clock cycles may also increase the clock cycle time.

EXAMPLE

Improving Performance

Our favorite program runs in 10 seconds on computer A, which has a 2 GHz clock. We are trying to help a computer designer build a computer, B, which will run this program in 6 seconds. The designer has determined that a substantial increase in the clock rate is possible, but this increase will affect the rest of the CPU design, causing computer B to require 1.2 times as many clock cycles as computer A for this program. What clock rate should we tell the designer to target?

Let's first find the number of clock cycles required for the program on A:

ANSWER

$$\text{CPU time}_A = \frac{\text{CPU clock cycles}_A}{\text{Clock rate}_A}$$

$$10 \text{ seconds} = \frac{\text{CPU clock cycles}_A}{2 \times 10^9 \frac{\text{cycles}}{\text{second}}}$$

$$\text{CPU clock cycles}_A = 10 \text{ seconds} \times 2 \times 10^9 \frac{\text{cycles}}{\text{second}} = 20 \times 10^9 \text{ cycles}$$

CPU time for B can be found using this equation:

$$\text{CPU time}_B = \frac{1.2 \times \text{CPU clock cycles}_A}{\text{Clock rate}_B}$$

$$6 \text{ seconds} = \frac{1.2 \times 20 \times 10^9 \text{ cycles}}{\text{Clock rate}_B}$$

$$\text{Clock rate}_B = \frac{1.2 \times 20 \times 10^9 \text{ cycles}}{6 \text{ seconds}} = \frac{0.2 \times 20 \times 10^9 \text{ cycles}}{\text{second}} = \frac{4 \times 10^9 \text{ cycles}}{\text{second}} = 4 \text{ GHz}$$

To run the program in 6 seconds, B must have twice the clock rate of A.

Instruction Performance

The performance equations above did not include any reference to the number of instructions needed for the program. (We'll see what the instructions that make up a program look like in the next chapter.) However, since the compiler clearly generated instructions to execute, and the computer had to execute the instructions to run the program, the execution time must depend on the number of instructions in a program. One way to think about execution time is that it equals the number of instructions executed multiplied by the average time per instruction. Therefore, the number of clock cycles required for a program can be written as

$$\text{CPU clock cycles} = \text{Instructions for a program} \times \frac{\text{Average clock cycles}}{\text{per instruction}}$$

The term **clock cycles per instruction**, which is the average number of clock cycles each instruction takes to execute, is often abbreviated as **CPI**. Since different

clock cycles per instruction (CPI)
Average number of clock cycles per instruction for a program or program fragment.

instructions may take different amounts of time depending on what they do, CPI is an average of all the instructions executed in the program. CPI provides one way of comparing two different implementations of the same instruction set architecture, since the number of instructions executed for a program will, of course, be the same.

EXAMPLE

ANSWER

Using the Performance Equation

Suppose we have two implementations of the same instruction set architecture. Computer A has a clock cycle time of 250 ps and a CPI of 2.0 for some program, and computer B has a clock cycle time of 500 ps and a CPI of 1.2 for the same program. Which computer is faster for this program and by how much?

We know that each computer executes the same number of instructions for the program; let's call this number I . First, find the number of processor clock cycles for each computer:

$$\text{CPU clock cycles}_A = I \times 2.0$$

$$\text{CPU clock cycles}_B = I \times 1.2$$

Now we can compute the CPU time for each computer:

$$\begin{aligned}\text{CPU time}_A &= \text{CPU clock cycles}_A \times \text{Clock cycle time} \\ &= I \times 2.0 \times 250 \text{ ps} = 500 \times I \text{ ps}\end{aligned}$$

Likewise, for B:

$$\text{CPU time}_B = I \times 1.2 \times 500 \text{ ps} = 600 \times I \text{ ps}$$

Clearly, computer A is faster. The amount faster is given by the ratio of the execution times:

$$\frac{\text{CPU performance}_A}{\text{CPU performance}_B} = \frac{\text{Execution time}_B}{\text{Execution time}_A} = \frac{600 \times I \text{ ps}}{500 \times I \text{ ps}} = 1.2$$

We can conclude that computer A is 1.2 times as fast as computer B for this program.

The Classic CPU Performance Equation

We can now write this basic performance equation in terms of **instruction count** (the number of instructions executed by the program), CPI, and clock cycle time:

$$\text{CPU time} = \text{Instruction count} \times \text{CPI} \times \text{Clock cycle time}$$

instruction count The number of instructions executed by the program.

or, since the clock rate is the inverse of clock cycle time:

$$\text{CPU time} = \frac{\text{Instruction count} \times \text{CPI}}{\text{Clock rate}}$$

These formulas are particularly useful because they separate the three key factors that affect performance. We can use these formulas to compare two different implementations or to evaluate a design alternative if we know its impact on these three parameters.

Comparing Code Segments

A compiler designer is trying to decide between two code sequences for a particular computer. The hardware designers have supplied the following facts:

EXAMPLE

	CPI for each instruction class		
	A	B	C
CPI	1	2	3

For a particular high-level language statement, the compiler writer is considering two code sequences that require the following instruction counts:

Code sequence	Instruction counts for each instruction class		
	A	B	C
1	2	1	2
2	4	1	1

Which code sequence executes the most instructions? Which will be faster? What is the CPI for each sequence?

ANSWER

Sequence 1 executes $2 + 1 + 2 = 5$ instructions. Sequence 2 executes $4 + 1 + 1 = 6$ instructions. Therefore, sequence 1 executes fewer instructions.

We can use the equation for CPU clock cycles based on instruction count and CPI to find the total number of clock cycles for each sequence:

$$\text{CPU clock cycles} = \sum_{i=1}^n (\text{CPI}_i \times C_i)$$

This yields

$$\text{CPU clock cycles}_1 = (2 \times 1) + (1 \times 2) + (2 \times 3) = 2 + 2 + 6 = 10 \text{ cycles}$$

$$\text{CPU clock cycles}_2 = (4 \times 1) + (1 \times 2) + (1 \times 3) = 4 + 2 + 3 = 9 \text{ cycles}$$

So code sequence 2 is faster, even though it executes one extra instruction. Since code sequence 2 takes fewer overall clock cycles but has more instructions, it must have a lower CPI. The CPI values can be computed by

$$\text{CPI} = \frac{\text{CPU clock cycles}}{\text{Instruction count}}$$

$$\text{CPI}_1 = \frac{\text{CPU clock cycles}_1}{\text{Instruction count}_1} = \frac{10}{5} = 2.0$$

$$\text{CPI}_2 = \frac{\text{CPU clock cycles}_2}{\text{Instruction count}_2} = \frac{9}{6} = 1.5$$

Figure 1.14 shows the basic measurements at different levels in the computer and what is being measured in each case. We can see how these factors are combined to yield execution time measured in seconds per program:

$$\text{Time} = \frac{\text{Instructions}}{\text{Program}} \times \frac{\text{Clock cycles}}{\text{Instruction}} \times \frac{\text{Seconds}}{\text{Clock cycle}}$$

Always bear in mind that the only complete and reliable measure of computer performance is time. For example, changing the instruction set to lower the instruction count may lead to an organization with a slower clock cycle time or higher CPI that offsets the improvement in instruction count. Similarly, because CPI depends on type of instructions executed, the code that executes the fewest number of instructions may not be the fastest.

The BIG Picture

Components of performance	Units of measure
CPU execution time for a program	Seconds for the program
Instruction count	Instructions executed for the program
Clock cycles per instruction (CPI)	Average number of clock cycles per instruction
Clock cycle time	Seconds per clock cycle

FIGURE 1.14 The basic components of performance and how each is measured.

How can we determine the value of these factors in the performance equation? We can measure the CPU execution time by running the program, and the clock cycle time is usually published as part of the documentation for a computer. The instruction count and CPI can be more difficult to obtain. Of course, if we know the clock rate and CPU execution time, we need only one of the instruction count or the CPI to determine the other.

We can measure the instruction count by using software tools that profile the execution or by using a simulator of the architecture. Alternatively, we can use hardware counters, which are included in most processors, to record a variety of measurements, including the number of instructions executed, the average CPI, and often, the sources of performance loss. Since the instruction count depends on the architecture, but not on the exact implementation, we can measure the instruction count without knowing all the details of the implementation. The CPI, however, depends on a wide variety of design details in the computer, including both the memory system and the processor structure (as we will see in Chapters 4 and 5), as well as on the mix of instruction types executed in an application. Thus, CPI varies by application, as well as among implementations with the same instruction set.

The above example shows the danger of using only one factor (instruction count) to assess performance. When comparing two computers, you must look at all three components, which combine to form execution time. If some of the factors are identical, like the clock rate in the above example, performance can be determined by comparing all the nonidentical factors. Since CPI varies by **instruction mix**, both instruction count and CPI must be compared, even if clock rates are identical. Several exercises at the end of this chapter ask you to evaluate a series of computer and compiler enhancements that affect clock rate, CPI, and instruction count. In Section 1.8, we'll examine a common performance measurement that does not incorporate all the terms and can thus be misleading.

instruction mix
A measure of the dynamic frequency of instructions across one or many programs.

Understanding Program Performance

The performance of a program depends on the algorithm, the language, the compiler, the architecture, and the actual hardware. The following table summarizes how these components affect the factors in the CPU performance equation.

Hardware or software component	Affects what?	How?
Algorithm	Instruction count, possibly CPI	The algorithm determines the number of source program instructions executed and hence the number of processor instructions executed. The algorithm may also affect the CPI, by favoring slower or faster instructions. For example, if the algorithm uses more floating-point operations, it will tend to have a higher CPI.
Programming language	Instruction count, CPI	The programming language certainly affects the instruction count, since statements in the language are translated to processor instructions, which determine instruction count. The language may also affect the CPI because of its features; for example, a language with heavy support for data abstraction (e.g., Java) will require indirect calls, which will use higher CPI instructions.
Compiler	Instruction count, CPI	The efficiency of the compiler affects both the instruction count and average cycles per instruction, since the compiler determines the translation of the source language instructions into computer instructions. The compiler's role can be very complex and affect the CPI in complex ways.
Instruction set architecture	Instruction count, clock rate, CPI	The instruction set architecture affects all three aspects of CPU performance, since it affects the instructions needed for a function, the cost in cycles of each instruction, and the overall clock rate of the processor.

Elaboration: Although you might expect that the minimum CPI is 1.0, as we'll see in Chapter 4, some processors fetch and execute multiple instructions per clock cycle. To reflect that approach, some designers invert CPI to talk about *IPC*, or *instruction per clock cycle*. If a processor executes on average 2 instructions per clock cycle, then it has an IPC of 2 and hence a CPI of 0.5.

Check Yourself

A given application written in Java runs 15 seconds on a desktop processor. A new Java compiler is released that requires only 0.6 as many instructions as the old compiler. Unfortunately, it increases the CPI by 1.1. How fast can we expect the application to run using this new compiler? Pick the right answer from the three choices below

- a. $\frac{15 \times 0.6}{1.1} = 8.2 \text{ sec}$
- b. $15 \times 0.6 \times 1.1 = 9.9 \text{ sec}$
- c. $\frac{15 \times 1.1}{0.6} = 27.5 \text{ sec}$

1.5 The Power Wall

Figure 1.15 shows the increase in clock rate and power of eight generations of Intel microprocessors over 25 years. Both clock rate and power increased rapidly for decades, and then flattened off recently. The reason they grew together is that they are correlated, and the reason for their recent slowing is that we have run into the practical power limit for cooling commodity microprocessors.

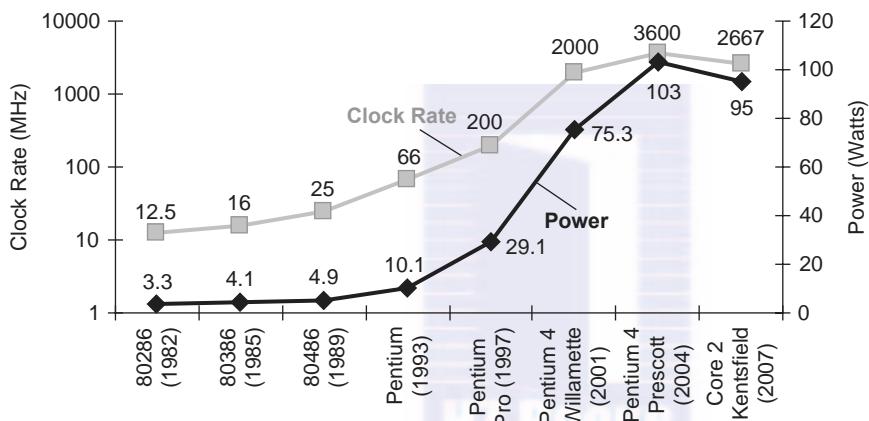


FIGURE 1.15 Clock rate and Power for Intel x86 microprocessors over eight generations and 25 years. The Pentium 4 made a dramatic jump in clock rate and power but less so in performance. The Prescott thermal problems led to the abandonment of the Pentium 4 line. The Core 2 line reverts to a simpler pipeline with lower clock rates and multiple processors per chip.

The dominant technology for integrated circuits is called CMOS (complementary metal oxide semiconductor). For CMOS, the primary source of power dissipation is so-called dynamic power—that is, power that is consumed during switching. The dynamic power dissipation depends on the capacitive loading of each transistor, the voltage applied, and the frequency that the transistor is switched:

$$\text{Power} = \text{Capacitive load} \times \text{Voltage}^2 \times \text{Frequency switched}$$

Frequency switched is a function of the clock rate. The capacitive load per transistor is a function of both the number of transistors connected to an output (called the *fanout*) and the technology, which determines the capacitance of both wires and transistors.

How could clock rates grow by a factor of 1000 while power grew by only a factor of 30? Power can be reduced by lowering the voltage, which occurred with each new generation of technology, and power is a function of the voltage squared. Typically, the voltage was reduced about 15% per generation. In 20 years, voltages have gone from 5V to 1V, which is why the increase in power is only 30 times.

EXAMPLE

ANSWER

Relative Power

Suppose we developed a new, simpler processor that has 85% of the capacitive load of the more complex older processor. Further, assume that it has adjustable voltage so that it can reduce voltage 15% compared to processor B, which results in a 15% shrink in frequency. What is the impact on dynamic power?

$$\frac{\text{Power}_{\text{new}}}{\text{Power}_{\text{old}}} = \frac{\langle \text{Capacitive load} \times 0.85 \rangle \times \langle \text{Voltage} \times 0.85 \rangle^2 \times \langle \text{Frequency switched} \times 0.85 \rangle}{\text{Capacitive load} \times \text{Voltage}^2 \times \text{Frequency switched}}$$

Thus the power ratio is

$$0.85^4 = 0.52$$

Hence, the new processor uses about half the power of the old processor.

The problem today is that further lowering of the voltage appears to make the transistors too leaky, like water faucets that cannot be completely shut off. Even today about 40% of the power consumption is due to leakage. If transistors started leaking more, the whole process could become unwieldy.

To try to address the power problem, designers have already attached large devices to increase cooling, and they turn off parts of the chip that are not used in a given clock cycle. Although there are many more expensive ways to cool chips and thereby raise their power to, say, 300 watts, these techniques are too expensive for desktop computers.

Since computer designers slammed into a power wall, they needed a new way forward. They chose a different way from the way they designed microprocessors for their first 30 years.

Elaboration: Although dynamic power is the primary source of power dissipation in CMOS, static power dissipation occurs because of leakage current that flows even when a transistor is off. As mentioned above, leakage is typically responsible for 40% of the power consumption in 2008. Thus, increasing the number of transistors increases power dissipation, even if the transistors are always off. A variety of design techniques and technology innovations are being deployed to control leakage, but it's hard to lower voltage further.

1.6

The Sea Change: The Switch from Uniprocessors to Multiprocessors

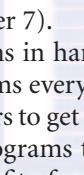
The power limit has forced a dramatic change in the design of microprocessors. Figure 1.16 shows the improvement in response time of programs for desktop microprocessors over time. Since 2002, the rate has slowed from a factor of 1.5 per year to less than a factor of 1.2 per year.

Rather than continuing to decrease the response time of a single program running on the single processor, as of 2006 all desktop and server companies are shipping microprocessors with multiple processors per chip, where the benefit is often more on throughput than on response time. To reduce confusion between the words processor and microprocessor, companies refer to processors as “cores,” and such microprocessors are generically called multicore microprocessors. Hence, a “quadcore” microprocessor is a chip that contains four processors or four cores.

Figure 1.17 shows the number of processors (cores), power, and clock rates of recent microprocessors. The official plan of record for many companies is to double the number of cores per microprocessor per semiconductor technology generation, which is about every two years (see Chapter 7).

In the past, programmers could rely on innovations in hardware, architecture, and compilers to double performance of their programs every 18 months without having to change a line of code. Today, for programmers to get significant improvement in response time, they need to rewrite their programs to take advantage of multiple processors. Moreover, to get the historic benefit of running faster on new microprocessors, programmers will have to continue to improve performance of their code as the number of cores doubles.

To reinforce how the software and hardware systems work hand in hand, we use a special section, *Hardware/Software Interface*, throughout the book, with the first one appearing below. These elements summarize important insights at this critical interface.

Up to now, most software has been like music written for a solo performer; with the current generation of chips we’re getting a little experience with duets and quartets and other small ensembles; but scoring a work for large orchestra and chorus is a different kind of challenge. 

Brian Hayes, *Computing in a Parallel Universe*, 2007.

Parallelism has always been critical to performance in computing, but it was often hidden. Chapter 4 will explain pipelining, an elegant technique that runs programs faster by overlapping the execution of instructions. This is one example of *instruction-level parallelism*, where the parallel nature of the hardware is abstracted away so the programmer and compiler can think of the hardware as executing instructions sequentially.

Forcing programmers to be aware of the parallel hardware and to explicitly rewrite their programs to be parallel had been the “third rail” of computer architecture, for companies in the past that depended on such a change in behavior failed (see Section 7.14 on the CD). From this historical perspective, it’s startling that the whole IT industry has bet its future that programmers will finally successfully switch to explicitly parallel programming.

Hardware/ Software Interface

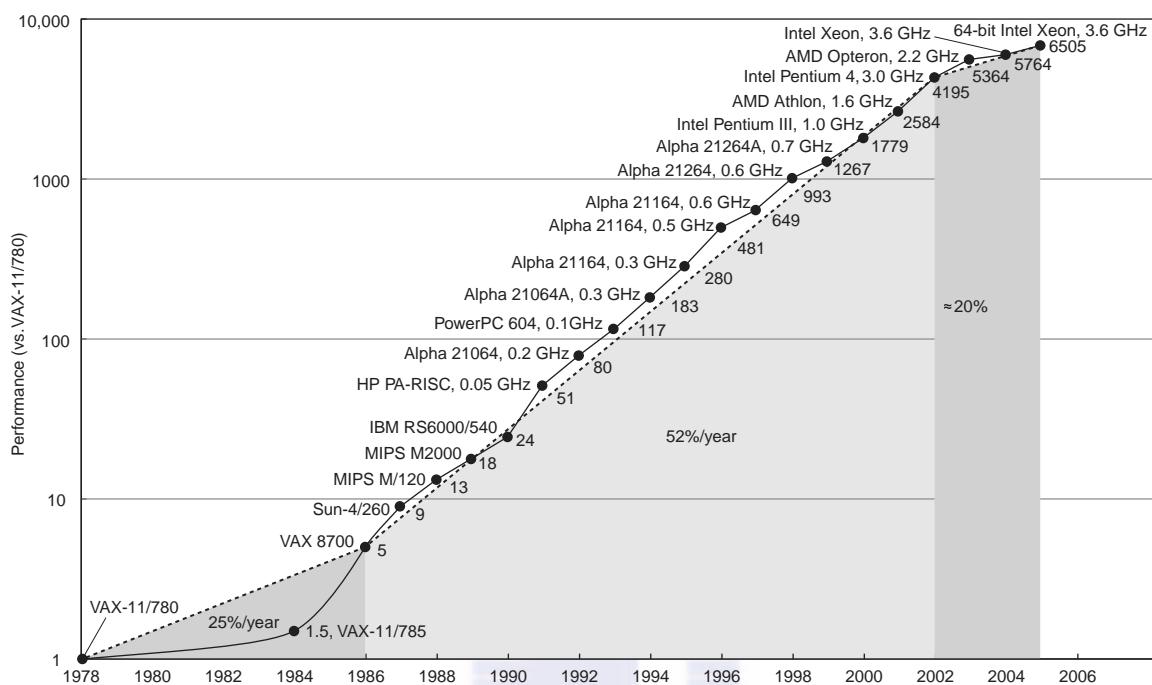


FIGURE 1.16 Growth in processor performance since the mid-1980s. This chart plots performance relative to the VAX 11/780 as measured by the SPECint benchmarks (see Section 1.8). Prior to the mid-1980s, processor performance growth was largely technology-driven and averaged about 25% per year. The increase in growth to about 52% since then is attributable to more advanced architectural and organizational ideas. By 2002, this growth led to a difference in performance of about a factor of seven. Performance for floating-point-oriented calculations has increased even faster. Since 2002, the limits of power, available instruction-level parallelism, and long memory latency have slowed uniprocessor performance recently, to about 20% per year.

Product	AMD Opteron X4 (Barcelona)	Intel Nehalem	IBM Power 6	Sun Ultra SPARC T2 (Niagara 2)
Cores per chip	4	4	2	8
Clock rate	2.5 GHz	~ 2.5 GHz ?	4.7 GHz	1.4 GHz
Microprocessor power	120 W	~ 100 W ?	~ 100 W ?	94 W

FIGURE 1.17 Number of cores per chip, clock rate, and power for 2008 multicore microprocessors.

Why has it been so hard for programmers to write explicitly parallel programs? The first reason is that parallel programming is by definition performance programming, which increases the difficulty of programming. Not only does the program need to be correct, solve an important problem, and provide a useful interface to the people or other programs that invoke it, the program must also be fast. Otherwise, if you don't need performance, just write a sequential program.

The second reason is that fast for parallel hardware means that the programmer must divide an application so that each processor has roughly the same amount to

do at the same time, and that the overhead of scheduling and coordination doesn't fritter away the potential performance benefits of parallelism.

As an analogy, suppose the task was to write a newspaper story. Eight reporters working on the same story could potentially write a story eight times faster. To achieve this increased speed, one would need to break up the task so that each reporter had something to do at the same time. Thus, we must *schedule* the sub-tasks. If anything went wrong and just one reporter took longer than the seven others did, then the benefits of having eight writers would be diminished. Thus, we must *balance the load* evenly to get the desired speedup. Another danger would be if reporters had to spend a lot of time talking to each other to write their sections. You would also fall short if one part of the story, such as the conclusion, couldn't be written until all of the other parts were completed. Thus, care must be taken to *reduce communication and synchronization overhead*. For both this analogy and parallel programming, the challenges include scheduling, load balancing, time for synchronization, and overhead for communication between the parties. As you might guess, the challenge is stiffer with more reporters for a newspaper story and more processors for parallel programming.

To reflect this sea change in the industry, the next five chapters in this edition of the book each have a section on the implications of the parallel revolution to that chapter:

- *Chapter 2, Section 2.11: Parallelism and Instructions: Synchronization.* Usually independent parallel tasks need to coordinate at times, such as to say when they have completed their work. This chapter explains the instructions used by multicore processors to synchronize tasks.
- *Chapter 3, Section 3.6: Parallelism and Computer Arithmetic: Associativity.* Often parallel programmers start from a working sequential program. A natural question to learn if their parallel version works is, "does it get the same answer?" If not, a logical conclusion is that there are bugs in the new version. This logic assumes that computer arithmetic is associative: you get the same sum when adding a million numbers, no matter what the order. This chapter explains that while this logic holds for integers, it doesn't hold for floating-point numbers.
- *Chapter 4, Section 4.10: Parallelism and Advanced Instruction-Level Parallelism.* Given the difficulty of explicitly parallel programming, tremendous effort was invested in the 1990s in having the hardware and the compiler uncover implicit parallelism. This chapter describes some of these aggressive techniques, including fetching and executing multiple instructions simultaneously and guessing on the outcomes of decisions, and executing instructions speculatively.

- *Chapter 5, Section 5.8: Parallelism and Memory Hierarchies: Cache Coherence.* One way to lower the cost of communication is to have all processors use the same address space, so that any processor can read or write any data. Given that all processors today use caches to keep a temporary copy of the data in faster memory near the processor, it's easy to imagine that parallel programming would be even more difficult if the caches associated with each processor had inconsistent values of the shared data. This chapter describes the mechanisms that keep the data in all caches consistent.
- *Chapter 6, Section 6.9: Parallelism and I/O: Redundant Arrays of Inexpensive Disks.* If you ignore input and output in this parallel revolution, the unintended consequence of parallel programming may be to make your parallel program spend most of its time waiting for I/O. This chapter describes RAID, a technique to accelerate the performance of storage accesses. RAID points out another potential benefit of parallelism: by having many copies of resources, the system can continue to provide service despite a failure of one resource. Hence, RAID can improve both I/O performance and availability.

In addition to these sections, there is a full chapter on parallel processing. Chapter 7 goes into more detail on the challenges of parallel programming; presents the two contrasting approaches to communication of shared addressing and explicit message passing; describes a restricted model of parallelism that is easier to program; discusses the difficulty of benchmarking parallel processors; introduces a new simple performance model for multicore microprocessors and finally describes and evaluates four examples of multicore microprocessors using this model.

Starting with this edition of the book, Appendix A describes an increasingly popular hardware component that is included with desktop computers, the graphics processing unit (GPU). Invented to accelerate graphics, GPUs are becoming programming platforms in their own right. As you might expect, given these times, GPUs are highly parallel. Appendix A describes the NVIDIA GPU and highlights parts of its parallel programming environment.

I thought [computers] would be a universally applicable idea, like a book is. But I didn't think it would develop as fast as it did, because I didn't envision we'd be able to get as many parts on a chip as we finally got. The transistor came along unexpectedly. It all happened much faster than we expected.
J. Presper Eckert,
coinventor of ENIAC,
speaking in 1991

1.7

Real Stuff: Manufacturing and Benchmarking the AMD Opteron X4

Each chapter has a section entitled “Real Stuff” that ties the concepts in the book with a computer you may use every day. These sections cover the technology underlying modern computers. For this first “Real Stuff” section, we look at how integrated circuits are manufactured and how performance and power are measured, with the AMD Opteron X4 as the example.

Let's start at the beginning. The manufacture of a chip begins with **silicon**, a substance found in sand. Because silicon does not conduct electricity well, it is called a **semiconductor**. With a special chemical process, it is possible to add materials to silicon that allow tiny areas to transform into one of three devices:

- Excellent conductors of electricity (using either microscopic copper or aluminum wire)
- Excellent insulators from electricity (like plastic sheathing or glass)
- Areas that can conduct *or* insulate under special conditions (as a switch)

Transistors fall in the last category. A VLSI circuit, then, is just billions of combinations of conductors, insulators, and switches manufactured in a single small package.

The manufacturing process for integrated circuits is critical to the cost of the chips and hence important to computer designers. Figure 1.18 shows that process. The process starts with a **silicon crystal ingot**, which looks like a giant sausage. Today, ingots are 8–12 inches in diameter and about 12–24 inches long. An ingot is finely sliced into **wafers** no more than 0.1 inch thick. These wafers then go through a series of processing steps, during which patterns of chemicals are placed on

silicon A natural element that is a semiconductor.

semiconductor
A substance that does not conduct electricity well.

silicon crystal ingot
A rod composed of a silicon crystal that is between 8 and 12 inches in diameter and about 12 to 24 inches long.

wafer A slice from a silicon ingot no more than 0.1 inch thick, used to create chips.

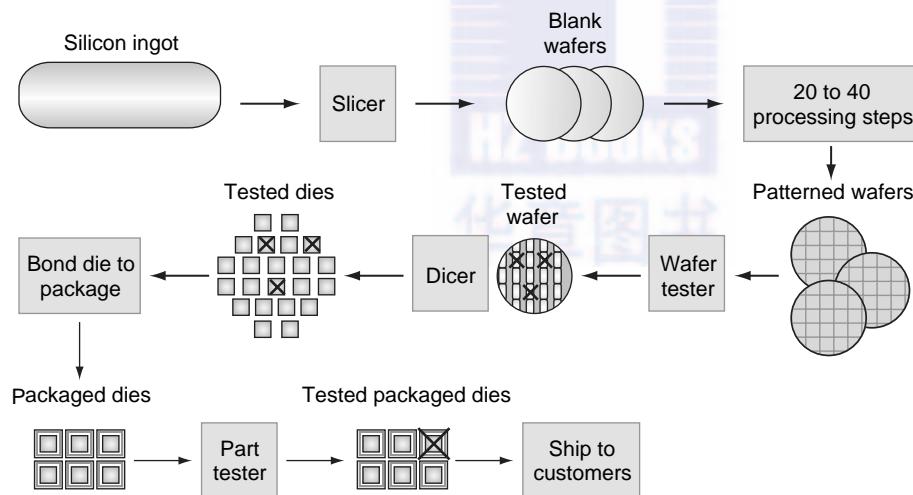


FIGURE 1.18 The chip manufacturing process. After being sliced from the silicon ingot, blank wafers are put through 20 to 40 steps to create patterned wafers (see Figure 1.19). These patterned wafers are then tested with a wafer tester, and a map of the good parts is made. Then, the wafers are diced into dies (see Figure 1.19). In this figure, one wafer produced 20 dies, of which 17 passed testing. (X means the die is bad.) The yield of good dies in this case was 17/20, or 85%. These good dies are then bonded into packages and tested one more time before shipping the packaged parts to customers. One bad packaged part was found in this final test.

each wafer, creating the transistors, conductors, and insulators discussed earlier. Today's integrated circuits contain only one layer of transistors but may have from two to eight levels of metal conductor, separated by layers of insulators.

defect A microscopic flaw in a wafer or in patterning steps that can result in the failure of the die containing that defect.

die The individual rectangular sections that are cut from a wafer, more informally known as **chips**.

yield The percentage of good dies from the total number of dies on the wafer.

A single microscopic flaw in the wafer itself or in one of the dozens of patterning steps can result in that area of the wafer failing. These **defects**, as they are called, make it virtually impossible to manufacture a perfect wafer. To cope with imperfection, several strategies have been used, but the simplest is to place many independent components on a single wafer. The patterned wafer is then chopped up, or *diced*, into these components, called **dies** and more informally known as **chips**. Figure 1.19 is a photograph of a wafer containing microprocessors before they have been diced; earlier, Figure 1.9 on page 20 shows an individual microprocessor die and its major components.

Dicing enables you to discard only those dies that were unlucky enough to contain the flaws, rather than the whole wafer. This concept is quantified by the **yield** of a process, which is defined as the percentage of good dies from the total number of dies on the wafer.

The cost of an integrated circuit rises quickly as the die size increases, due both to the lower yield and the smaller number of dies that fit on a wafer. To reduce the cost, a large die is often “shrunk” by using the next generation process, which incorporates smaller sizes for both transistors and wires. This improves the yield and the die count per wafer.

Once you've found good dies, they are connected to the input/output pins of a package, using a process called *bonding*. These packaged parts are tested a final time, since mistakes can occur in packaging, and then they are shipped to customers.

As mentioned above, an increasingly important design constraint is power. Power is a challenge for two reasons. First, power must be brought in and distributed around the chip; modern microprocessors use hundreds of pins just for power and ground! Similarly, multiple levels of interconnect are used solely for power and ground distribution to portions of the chip. Second, power is dissipated as heat and must be removed. An AMD Opteron X4 model 2356 2.0 GHz burns 120 watts in 2008, which must be removed from a chip whose surface area is just over 1 cm²!

Elaboration: The cost of an integrated circuit can be expressed in three simple equations:

$$\text{Cost per die} = \frac{\text{Cost per wafer}}{\text{Dies per wafer} \times \text{yield}}$$

$$\begin{aligned}\text{Dies per wafer} &\approx \frac{\text{Wafer area}}{\text{Die area}} \\ &= \frac{1}{(1 + (\text{Defects per area} \times \text{Die area}/2))^2}\end{aligned}$$

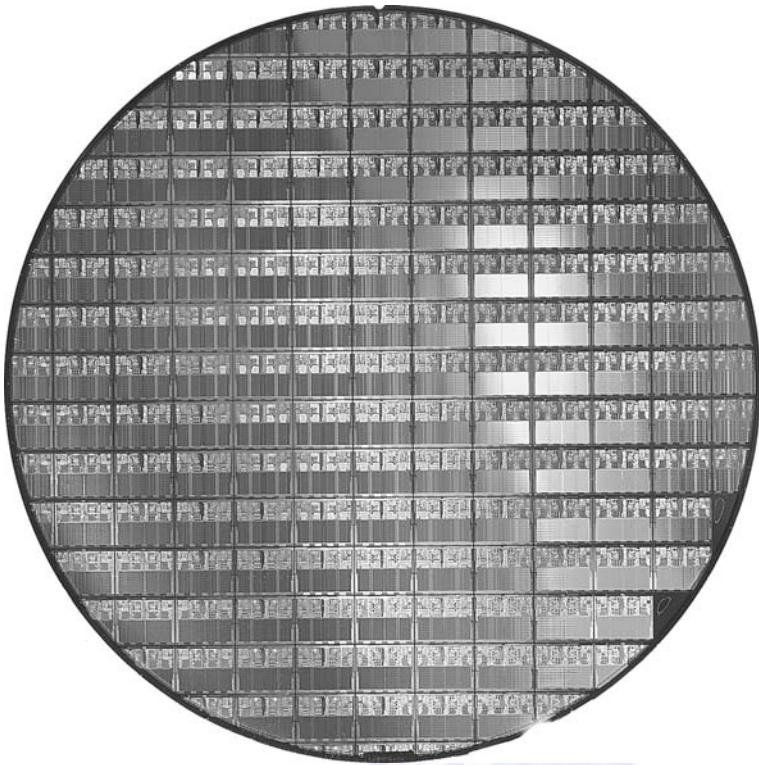


FIGURE 1.19 A 12-inch (300mm) wafer of AMD Opteron X2 chips, the predecessor of Opteron X4 chips (Courtesy AMD). The number of dies per wafer at 100% yield is 117. The several dozen partially rounded chips at the boundaries of the wafer are useless; they are included because it's easier to create the masks used to pattern the silicon. This die uses a 90-nanometer technology, which means that the smallest transistors are approximately 90 nm in size, although they are typically somewhat smaller than the actual feature size, which refers to the size of the transistors as "drawn" versus the final manufactured size.

The first equation is straightforward to derive. The second is an approximation, since it does not subtract the area near the border of the round wafer that cannot accommodate the rectangular dies (see Figure 1.19). The final equation is based on empirical observations of yields at integrated circuit factories, with the exponent related to the number of critical processing steps.

Hence, depending on the defect rate and the size of the die and wafer, costs are generally not linear in die area.

SPEC CPU Benchmark

workload A set of programs run on a computer that is either the actual collection of applications run by a user or constructed from real programs to approximate such a mix. A typical workload specifies both the programs and the relative frequencies.

benchmark A program selected for use in comparing computer performance.

A computer user who runs the same programs day in and day out would be the perfect candidate to evaluate a new computer. The set of programs run would form a **workload**. To evaluate two computer systems, a user would simply compare the execution time of the workload on the two computers. Most users, however, are not in this situation. Instead, they must rely on other methods that measure the performance of a candidate computer, hoping that the methods will reflect how well the computer will perform with the user's workload. This alternative is usually followed by evaluating the computer using a set of **benchmarks**—programs specifically chosen to measure performance. The benchmarks form a workload that the user hopes will predict the performance of the actual workload.

SPEC (System Performance Evaluation Cooperative) is an effort funded and supported by a number of computer vendors to create standard sets of benchmarks for modern computer systems. In 1989, SPEC originally created a benchmark set focusing on processor performance (now called SPEC89), which has evolved through five generations. The latest is SPEC CPU2006, which consists of a set of 12 integer benchmarks (CINT2006) and 17 floating-point benchmarks (CFP2006). The integer benchmarks vary from part of a C compiler to a chess program to a quantum computer simulation. The floating-point benchmarks include structured grid codes for finite element modeling, particle method codes for molecular dynamics, and sparse linear algebra codes for fluid dynamics.

Figure 1.20 describes the SPEC integer benchmarks and their execution time on the Opteron X4 and shows the factors that explain execution time: instruction count, CPI, and clock cycle time. Note that CPI varies by a factor of 13.

To simplify the marketing of computers, SPEC decided to report a single number to summarize all 12 integer benchmarks. The execution time measurements are first normalized by dividing the execution time on a reference processor by the execution time on the measured computer; this normalization yields a measure, called the *SPECratio*, which has the advantage that bigger numeric results indicate faster performance (i.e., the SPECratio is the inverse of execution time). A CINT2006 or CFP2006 summary measurement is obtained by taking the geometric mean of the SPECratios.

Elaboration: When comparing two computers using SPECratios, use the geometric mean so that it gives the same relative answer no matter what computer is used to normalize the results. If we average the normalized execution time values with an arithmetic mean, the results would vary depending on the computer we choose as the reference.

Description	Name	Instruction Count $\times 10^9$	CPI	Clock cycle time (seconds $\times 10^9$)	Execution Time (seconds)	Reference Time (seconds)	SPECratio
Interpreted string processing	perl	2,118	0.75	0.4	637	9,770	15.3
Block-sorting compression	bzip2	2,389	0.85	0.4	817	9,650	11.8
GNU C compiler	gcc	1,050	1.72	0.4	724	8,050	11.1
Combinatorial optimization	mcf	336	10.00	0.4	1,345	9,120	6.8
Go game (AI)	go	1,658	1.09	0.4	721	10,490	14.6
Search gene sequence	hmmer	2,783	0.80	0.4	890	9,330	10.5
Chess game (AI)	sjeng	2,176	0.96	0.4	837	12,100	14.5
Quantum computer simulation	libquantum	1,623	1.61	0.4	1,047	20,720	19.8
Video compression	h264avc	3,102	0.80	0.4	993	22,130	22.3
Discrete event simulation library	omnetpp	587	2.94	0.4	690	6,250	9.1
Games/path finding	astar	1,082	1.79	0.4	773	7,020	9.1
XML parsing	xalancbmk	1,058	2.70	0.4	1,143	6,900	6.0
Geometric Mean							11.7

FIGURE 1.20 SPECINTC2006 benchmarks running on AMD Opteron X4 model 2356 (Barcelona). As the equation on page 35 explains, execution time is the product of the three factors in this table: instruction count in billions, clocks per instruction (CPI), and clock cycle time in nanoseconds. SPECratio is simply the reference time, which is supplied by SPEC, divided by the measured execution time. The single number quoted as SPECINTC2006 is the geometric mean of the SPECratios. Figure 5.40 on page 542 shows that mcf, libquantum, omnetpp, and xalancbmk have relatively high CPIs because they have high cache miss rates.

The formula for the geometric mean is

$$\sqrt[n]{\prod_{i=1}^n \text{Execution time ratio}_i}$$

where $\text{Execution time ratio}_i$ is the execution time, normalized to the reference computer, for the i th program of a total of n in the workload, and

$$\prod_{i=1}^n a_i \text{ means the product } a_1 \times a_2 \times \dots \times a_n$$

SPEC Power Benchmark

Today, SPEC offers a dozen different benchmark sets designed to test a wide variety of computing environments using real applications and strictly specified execution rules and reporting requirements. The most recent is SPECpower. It reports power consumption of servers at different workload levels, divided into 10% increments, over a period of time. Figure 1.21 shows the results for a server using Barcelona.

SPECpower started with the SPEC benchmark for Java business applications (SPECJBB2005), which exercises the processors, caches, and main memory as well as the Java virtual machine, compiler, garbage collector, and pieces of the operating

Target Load %	Performance (ssj_ops)	Average Power (Watts)
100%	231,867	295
90%	211,282	286
80%	185,803	275
70%	163,427	265
60%	140,160	256
50%	118,324	246
40%	92,035	233
30%	70,500	222
20%	47,126	206
10%	23,066	180
0%	0	141
Overall Sum	1,283,590	2,605
$\Sigma \text{ssj_ops} / \Sigma \text{power} =$		493

FIGURE 1.21 SPECpower_ssj2008 running on dual socket 2.3 GHz AMD Opteron X4 2356 (Barcelona) with 16 GB Of DDR2-667 DRAM and one 500 GB disk.

system. Performance is measured in throughput, and the units are business operations per second. Once again, to simplify the marketing of computers, SPEC boils these numbers down to a single number, called “overall ssj_ops per Watt.” The formula for this single summarizing metric is

$$\text{overall ssj_ops per Watt} = \left(\sum_{i=0}^{10} \text{ssj_ops}_i \right) / \left(\sum_{i=0}^{10} \text{power}_i \right)$$

where ssj_ops_i is performance at each 10% increment and power_i is power consumed at each performance level.

Check Yourself A key factor in determining the cost of an integrated circuit is volume. Which of the following are reasons why a chip made in high volume should cost less?

- With high volumes, the manufacturing process can be tuned to a particular design, increasing the yield.
- It is less work to design a high-volume part than a low-volume part.
- The masks used to make the chip are expensive, so the cost per chip is lower for higher volumes.
- Engineering development costs are high and largely independent of volume; thus, the development cost per die is lower with high-volume parts.
- High-volume parts usually have smaller die sizes than low-volume parts and therefore have higher yield per wafer.

1.8

Fallacies and Pitfalls

The purpose of a section on fallacies and pitfalls, which will be found in every chapter, is to explain some commonly held misconceptions that you might encounter. We call such misbeliefs *fallacies*. When discussing a fallacy, we try to give a counterexample. We also discuss *pitfalls*, or easily made mistakes. Often pitfalls are generalizations of principles that are true in a limited context. The purpose of these sections is to help you avoid making these mistakes in the computers you may design or use. Cost/performance fallacies and pitfalls have ensnared many a computer architect, including us. Accordingly, this section suffers no shortage of relevant examples. We start with a pitfall that traps many designers and reveals an important relationship in computer design.

Pitfall: Expecting the improvement of one aspect of a computer to increase overall performance by an amount proportional to the size of the improvement.

This pitfall has visited designers of both hardware and software. A simple design problem illustrates it well. Suppose a program runs in 100 seconds on a computer, with multiply operations responsible for 80 seconds of this time. How much do I have to improve the speed of multiplication if I want my program to run five times faster?

The execution time of the program after making the improvement is given by the following simple equation known as **Amdahl's law**:

$$\text{Execution time after improvement} =$$

$$\frac{\text{Execution time affected by improvement}}{\text{Amount of improvement}} + \text{Execution time unaffected}$$

For this problem:

$$\text{Execution time after improvement} = \frac{80 \text{ seconds}}{n} + (100 - 80 \text{ seconds})$$

Since we want the performance to be five times faster, the new execution time should be 20 seconds, giving

$$\begin{aligned} 20 \text{ seconds} &= \frac{80 \text{ seconds}}{n} + 20 \text{ seconds} \\ 0 &= \frac{80 \text{ seconds}}{n} \end{aligned}$$

That is, there is *no amount* by which we can enhance-multiply to achieve a fivefold increase in performance, if multiply accounts for only 80% of the workload.

Science must begin with myths, and the criticism of myths.

Sir Karl Popper, *The Philosophy of Science*, 1957

Amdahl's law A rule stating that the performance enhancement possible with a given improvement is limited by the amount that the improved feature is used. It is a quantitative version of the law of diminishing returns.

The performance enhancement possible with a given improvement is limited by the amount that the improved feature is used. This concept also yields what we call the law of diminishing returns in everyday life.

We can use Amdahl's law to estimate performance improvements when we know the time consumed for some function and its potential speedup. Amdahl's law, together with the CPU performance equation, is a handy tool for evaluating potential enhancements. Amdahl's law is explored in more detail in the exercises.

A common theme in hardware design is a corollary of Amdahl's law: *Make the common case fast*. This simple guideline reminds us that in many cases the frequency with which one event occurs may be much higher than the frequency of another. Amdahl's law reminds us that the opportunity for improvement is affected by how much time the event consumes. Thus, making the common case fast will tend to enhance performance better than optimizing the rare case. Ironically, the common case is often simpler than the rare case and hence is often easier to enhance.

Amdahl's law is also used to argue for practical limits to the number of parallel processors. We examine this argument in the Fallacies and Pitfalls section of Chapter 7.

Fallacy: Computers at low utilization use little power.

Power efficiency matters at low utilizations because server workloads vary. CPU utilization for servers at Google, for example, is between 10% and 50% most of the time and at 100% less than 1% of the time. Figure 1.22 shows power for servers with the best SPECpower results at 100% load, 50% load, 10% load, and idle. Even servers that are only 10% utilized burn about two-thirds of their peak power.

Since servers' workloads vary but use a large fraction of peak power, Luiz Barroso and Urs Hözle [2007] argue that we should redesign hardware to achieve "energy-proportional computing." If future servers used, say, 10% of peak power at 10% workload, we could reduce the electricity bill of datacenters and become good corporate citizens in an era of increasing concern about CO₂ emissions.

Server Manufacturer	Micro-processor	Total Cores/Sockets	Clock Rate	Peak Performance (ssj_ops)	100% Load Power	50% Load Power	50% Load/100% Power	10% Load Power	10% Load/100% Power	Active Idle Power	Active Idle/100% Power
HP	Xeon E5440	8/2	3.0 GHz	308,022	269 W	227 W	84%	174 W	65%	160 W	59%
Dell	Xeon E5440	8/2	2.8 GHz	305,413	276 W	230 W	83%	173 W	63%	157 W	57%
Fujitsu Siemens	Xeon X3220	4/1	2.4 GHz	143,742	132 W	110 W	83%	85 W	65%	80 W	60%

FIGURE 1.22 SPECPower results for three servers with the best overall ssj_ops per watt in the fourth quarter of 2007. The overall ssj_ops per watt of the three servers are 698, 682, and 667, respectively. The memory of the top two servers is 16 GB and the bottom is 8 GB.

Pitfall: Using a subset of the performance equation as a performance metric.

We have already shown the fallacy of predicting performance based on simply one of clock rate, instruction count, or CPI. Another common mistake is to use only

two of the three factors to compare performance. Although using two of the three factors may be valid in a limited context, the concept is also easily misused. Indeed, nearly all proposed alternatives to the use of time as the performance metric have led eventually to misleading claims, distorted results, or incorrect interpretations.

One alternative to time is **MIPS** (million instructions per second). For a given program, MIPS is simply

$$\text{MIPS} = \frac{\text{Instruction count}}{\text{Execution time} \times 10^6}$$

Since MIPS is an instruction execution rate, MIPS specifies performance inversely to execution time; faster computers have a higher MIPS rating. The good news about MIPS is that it is easy to understand, and faster computers mean bigger MIPS, which matches intuition.

There are three problems with using MIPS as a measure for comparing computers. First, MIPS specifies the instruction execution rate but does not take into account the capabilities of the instructions. We cannot compare computers with different instruction sets using MIPS, since the instruction counts will certainly differ. Second, MIPS varies between programs on the same computer; thus, a computer cannot have a single MIPS rating. For example, by substituting for execution time, we see the relationship between MIPS, clock rate, and CPI:

$$\text{MIPS} = \frac{\text{Instruction count}}{\frac{\text{Instruction count} \times \text{CPI}}{\text{Clock rate}} \times 10^6} = \frac{\text{Clock rate}}{\text{CPI} \times 10^6}$$

Recall that CPI varied by 13× for SPEC2006 on Opteron X4, so MIPS does as well. Finally, and most importantly, if a new program executes more instructions but each instruction is faster, MIPS can vary independently from performance!

Consider the following performance measurements for a program:

million instructions per second (MIPS)
A measurement of program execution speed based on the number of millions of instructions. MIPS is computed as the instruction count divided by the product of the execution time and 10^6 .

Measurement	Computer A	Computer B
Instruction count	10 billion	8 billion
Clock rate	4 GHz	4 GHz
CPI	1.0	1.1

Check Yourself

- Which computer has the higher MIPS rating?
- Which computer is faster?

Where . . . the ENIAC is equipped with 18,000 vacuum tubes and weighs 30 tons, computers in the future may have 1,000 vacuum tubes and perhaps weigh just 1½ tons.

Popular Mechanics,
March 1949

1.9

Concluding Remarks

Although it is difficult to predict exactly what level of cost/performance computers will have in the future, it's a safe bet that they will be much better than they are today. To participate in these advances, computer designers and programmers must understand a wider variety of issues.

Both hardware and software designers construct computer systems in hierarchical layers, with each lower layer hiding details from the level above. This principle of abstraction is fundamental to understanding today's computer systems, but it does not mean that designers can limit themselves to knowing a single abstraction. Perhaps the most important example of abstraction is the interface between hardware and low-level software, called the *instruction set architecture*. Maintaining the instruction set architecture as a constant enables many implementations of that architecture—presumably varying in cost and performance—to run identical software. On the downside, the architecture may preclude introducing innovations that require the interface to change.

There is a reliable method of determining and reporting performance by using the execution time of real programs as the metric. This execution time is related to other important measurements we can make by the following equation:

$$\frac{\text{Seconds}}{\text{Program}} = \frac{\text{Instructions}}{\text{Program}} \times \frac{\text{Clock cycles}}{\text{Instruction}} \times \frac{\text{Seconds}}{\text{Clock cycle}}$$

We will use this equation and its constituent factors many times. Remember, though, that individually the factors do not determine performance: only the product, which equals execution time, is a reliable measure of performance.

The BIG Picture

Execution time is the only valid and unimpeachable measure of performance. Many other metrics have been proposed and found wanting. Sometimes these metrics are flawed from the start by not reflecting execution time; other times a metric that is valid in a limited context is extended and used beyond that context or without the additional clarification needed to make it valid.

The key hardware technology for modern processors is silicon. Equal in importance to an understanding of integrated circuit technology is an understanding of the expected rates of technological change. While silicon fuels the rapid advance of hardware, new ideas in the organization of computers have improved price/performance. Two of the key ideas are exploiting parallelism in the program,

typically today via multiple processors, and exploiting locality of accesses to a memory hierarchy, typically via caches.

Power has replaced die area as the most critical resource of microprocessor design. Conserving power while trying to increase performance has forced the hardware industry to switch to multicore microprocessors, thereby forcing the software industry to switch to programming parallel hardware.

Computer designs have always been measured by cost and performance, as well as other important factors such as power, reliability, cost of ownership, and scalability. Although this chapter has focused on cost, performance, and power, the best designs will strike the appropriate balance for a given market among all the factors.

Road Map for This Book

At the bottom of these abstractions are the five classic components of a computer: datapath, control, memory, input, and output (refer to Figure 1.4). These five components also serve as the framework for the rest of the chapters in this book:

- *Datapath*: Chapters 3, 4, 7, and Appendix A
- *Control*: Chapters 4, 7, and Appendix A
- *Memory*: Chapter 5
- *Input*: Chapter 6
- *Output*: Chapter 6

As mentioned above, Chapter 4 describes how processors exploit implicit parallelism, Chapter 7 describes the explicitly parallel multicore microprocessors that are at the heart of the parallel revolution, and Appendix A describes the highly parallel graphics processor chip. Chapter 5 describes how a memory hierarchy exploits locality. Chapter 2 describes instruction sets—the interface between compilers and the computer—and emphasizes the role of compilers and programming languages in using the features of the instruction set. Appendix B provides a reference for the instruction set of Chapter 2. Chapter 3 describes how computers handle arithmetic data. ☺ Appendix C, on the CD, introduces logic design.

An active field of science is like an immense anthill; the individual almost vanishes into the mass of minds tumbling over each other, carrying information from place to place, passing it around at the speed of light.

Lewis Thomas, “Natural Science,” in *The Lives of a Cell*, 1974



Historical Perspective and Further Reading

For each chapter in the text, a section devoted to a historical perspective can be found on the CD that accompanies this book. We may trace the development of an idea through a series of computers or describe some important projects, and we provide references in case you are interested in probing further.

The historical perspective for this chapter provides a background for some of the key ideas presented in this opening chapter. Its purpose is to give you the human story behind the technological advances and to place achievements in their historical context. By understanding the past, you may be better able to understand the forces that will shape computing in the future. Each historical perspectives section on the CD ends with suggestions for further reading, which are also collected separately on the CD under the section “Further Reading.” The rest of  Section 1.10 is found on the CD.

1.11

Exercises

Contributed by Javier Bruguera of Universidade de Santiago de Compostela

Most of the exercises in this edition are designed so that they feature a qualitative description supported by a table that provides alternative quantitative parameters. These parameters are needed to solve the questions that comprise the exercise. Individual questions can be solved using any or all of the parameters—you decide how many of the parameters should be considered for any given exercise question. For example, it is possible to say “complete Question 4.1.1 using the parameters given in row A of the table.” Alternately, instructors can customize these exercises to create novel solutions by replacing the given parameters with your own unique values.

The number of quantitative exercises varies from chapter to chapter and depends largely on the topics covered. More conventional exercises are provided where the quantitative approach does not fit.

The relative time ratings of exercises are shown in square brackets after each exercise number. On average, an exercise rated [10] will take you twice as long as one rated [5]. Sections of the text that should be read before attempting an exercise will be given in angled brackets; for example, <1.3> means you should have read Section 1.3, Under the Covers, to help you solve this exercise.

Exercise 1.1

Find the word or phrase from the list below that best matches the description in the following questions. Use the numbers to the left of the words in the answer. Each answer should be used only once.

1.	virtual worlds	14.	operating system
2.	desktop computer s	15.	compiler
3.	servers	16.	bit
4.	low-end servers	17.	instruction
5.	supercomputers	18.	assembly language
6.	terabyte	19.	machine language
7.	petabyte	20.	C
8.	datacenters	21.	assembler
9.	embedded computers	22.	high-level language
10.	multicore processor s	23.	system software
11.	VHDL	24.	application software
12.	RAM	25.	cobol
13.	CPU	26.	fortran

1.1.1 [2] <1.1> Computer used to run large problems and usually accessed via a network

1.1.2 [2] <1.1> 10^{15} or 2^{50} bytes

1.1.3 [2] <1.1> Computer composed of hundreds to thousands of processors and terabytes of memory

1.1.4 [2] <1.1> Today's science fiction application that probably will be available in near future

1.1.5 [2] <1.1> A kind of memory called random access memory

1.1.6 [2] <1.1> Part of a computer called central processor unit

1.1.7 [2] <1.1> Thousands of processors forming a large cluster

1.1.8 [2] <1.1> A microprocessor containing several processors in the same chip

1.1.9 [2] <1.1> Desktop computer without screen or keyboard usually accessed via a network

1.1.10 [2] <1.1> Currently the largest class of computer that runs one application or one set of related applications

1.1.11 [2] <1.1> Special language used to describe hardware components

1.1.12 [2] <1.1> Personal computer delivering good performance to single users at low cost

1.1.13 [2] <1.2> Program that translates statements in high-level language to assembly language

1.1.14 [2] <1.2> Program that translates symbolic instructions to binary instructions

1.1.15 [2] <1.2> High-level language for business data processing

1.1.16 [2] <1.2> Binary language that the processor can understand

1.1.17 [2] <1.2> Commands that the processors understand

1.1.18 [2] <1.2> High-level language for scientific computation

1.1.19 [2] <1.2> Symbolic representation of machine instructions

1.1.20 [2] <1.2> Interface between user's program and hardware providing a variety of services and supervision functions

1.1.21 [2] <1.2> Software/programs developed by the users

1.1.22 [2] <1.2> Binary digit (value 0 or 1)

1.1.23 [2] <1.2> Software layer between the application software and the hardware that includes the operating system and the compilers

1.1.24 [2] <1.2> High-level language used to write application and system software

1.1.25 [2] <1.2> Portable language composed of words and algebraic expressions that must be translated into assembly language before run in a computer

1.1.26 [2] <1.2> 10^{12} or 2^{40} bytes

Exercise 1.2

1.2.1 [10] <1.3> For a color display using 8 bits for each of the primary colors (red, green, blue) per pixel and with a resolution of 1280×800 pixels, what should be the size (in bytes) of the frame buffer to store a frame?

1.2.2 [5] <1.3> If a computer has a main memory of 2 GB, how many frames could it store, assuming the memory contains no other information?

1.2.3 [5] <1.3> If a computer connected to a 1 gigabit Ethernet network needs to send a 256 Kbytes file, how long it would take?

1.2.4 [5] <1.3> Assuming that a cache memory is ten times faster than a DRAM memory, that DRAM is 100,000 times faster than magnetic disk, and that flash memory is 1000 times faster than disk, find how long it takes to read a file from a DRAM, a disk, and a flash memory if it takes 2 microseconds from the cache memory?

Exercise 1.3

Consider three different processors P1, P2, and P3 executing the same instruction set with the clock rates and CPIs given in the following table.

Processor	Clock rate	CPI
P1	2 GHz	1.5
P2	1.5 GHz	1.0
P3	3 GHz	2.5

1.3.1 [5] <1.4> Which processor has the highest performance?

1.3.2 [5] <1.4> If the processors each execute a program in 10 seconds, find the number of cycles and the number of instructions.

1.3.3 [10] <1.4> We are trying to reduce the time by 30% but this leads to an increase of 20% in the CPI. What clock rate should we have to get this time reduction?

For problems below, use the information in the following table.

Processor	Clock rate	No. instructions	Time
P1	2 GHz	20×10^9	7 s
P2	1.5 GHz	30×10^9	10 s
P3	3 GHz	90×10^9	9 s

1.3.4 [10] <1.4> Find the IPC (instructions per cycle) for each processor.

1.3.5 [5] <1.4> Find the clock rate for P2 that reduces its execution time to that of P1.

1.3.6 [5] <1.4> Find the number of instructions for P2 that reduces its execution time to that of P3.

Exercise 1.4

Consider two different implementations of the same instruction set architecture. There are four classes of instructions, A, B, C, and D. The clock rate and CPI of each implementation are given in the following table.

	Clock rate	CPI Class A	CPI Class B	CPI Class C	CPI Class D
P1	1.5 GHz	1 2 3			4
P2	2 GHz	2 2 2			2

1.4.1 [10] <1.4> Given a program with 10^6 instructions divided into classes as follows: 10% class A, 20% class B, 50% class C and 20% class D, which implementation is faster?

1.4.2 [5] <1.4> What is the global CPI for each implementation?

1.4.3 [5] <1.4> Find the clock cycles required in both cases.

The following table shows the number of instructions for a program.

Arith	Store	Load	Branch	Total
500 50		100 50		700

1.4.4 [5] <1.4> Assuming that arith instructions take 1 cycle, load and store 5 cycles and branch 2 cycles, what is the execution time of the program in a 2 GHz processor?

1.4.5 [5] <1.4> Find the CPI for the program.

1.4.6 [10] <1.4> If the number of load instructions can be reduced by one-half, what is the speed-up and the CPI?

Exercise 1.5

Consider two different implementations, P1 and P2, of the same instruction set. There are five classes of instructions (A, B, C, D, and E) in the instruction set. The clock rate and CPI of each class is given below.

		Clock rate	CPI Class A	CPI Class B	CPI Class C	CPI Class D	CPI Class E
a.	P1	1.0 GHz	1 2 3 4 3				
	P2	1.5 GHz	2 2 2 4 4				
b.	P1	1.0 GHz	1 1 2 3 2				
	P2	1.5 GHz	1 2 3 4 3				

1.5.1 [5] <1.4> Assume that peak performance is defined as the fastest rate that a computer can execute any instruction sequence. What are the peak performances of P1 and P2 expressed in instructions per second?

1.5.2 [5] <1.4> If the number of instructions executed in a certain program is divided equally among the classes of instructions except for class A, which occurs twice as often as each of the others. Which computer is faster? How much faster is it?

1.5.3 [5] <1.4> If the number of instructions executed in a certain program is divided equally among the classes of instructions except for class E, which occurs twice as often as each of the others? Which computer is faster? How much faster is it?

The table below shows instruction-type breakdown for different programs. Using this data, you will be exploring the performance tradeoffs with different changes made to a MIPS processor.

		# Instructions				
		Compute	Load	Store	Branch	Total
a.	Program 1	1000	400	100	50	1550
b.	Program 4	1500	300	100	100	1750

1.5.4 [5] <1.4> Assuming that computes take 1 cycle, loads and store instructions take 10 cycles, and branches take 3 cycles, find the execution time of each program on a 3 GHz MIPS processor.

1.5.5 [5] <1.4> Assuming that computes take 1 cycle, loads and store instructions take 2 cycles, and branches take 3 cycles, find the execution time of each program on a 3 GHz MIPS processor.

1.5.6 [5] <1.4> Assuming that computes take 1 cycle, loads and store instructions take 2 cycles, and branches take 3 cycles, what is the speed-up of a program if the number of compute instruction can be reduced by one-half?

Exercise 1.6

Compilers can have a profound impact on the performance of an application on a given processor. This problem will explore the impact compilers have on execution time.

	Compiler A		Compiler B	
	# Instructions	Execution time	# Instructions	Execution time
a.	1.00E+09	1 s	1.20E+09	1.4 s
b.	1.00E+09	0.8 s	1.20E+09	0.7 s

1.6.1 [5] <1.4> For the same program, two different compilers are used. The table above shows the execution time of the two different compiled programs. Find the average CPI for each program given that the processor has a clock cycle time of 1 nS.

1.6.2 [5] <1.4> Assume the average CPIs found in 1.6.1, but that the compiled programs run on two different processors. If the execution times on the two processors are the same, how much faster is the clock of the processor running compiler A's code versus the clock of the processor running compiler B's code?

1.6.3 [5] <1.4> A new compiler is developed that uses only 600 million instructions and has an average CPI of 1.1. What is the speed-up of using this new compiler versus using Compiler A or B on the original processor of 1.6.1?

Consider two different implementations, P1 and P2, of the same instruction set. There are five classes of instructions (A, B, C, D, and E) in the instruction set. P1 has a clock rate of 4 GHz, and P2 has a clock rate of 6 GHz. The average number of cycles for each instruction class for P1 and P2 are listed in the following table.

	Class	CPI on P1	CPI on P2
a.	A 1 2		
	B 2		2
	C 3		2
	D 4		4
	E 5 4		

	Class	CPI on P1	CPI on P2
b.	A 1 2		
	B 1		2
	C 1		2
	D 4		4
	E 5 4		

1.6.4 [5] <1.4> Assume that peak performance is defined as the fastest rate that a computer can execute any instruction sequence. What are the peak performances of P1 and P2 expressed in instructions per second?

1.6.5 [5] <1.4> If the number of instructions executed in a certain program is divided equally among the classes of instructions in Problem 2.36.4 except for class A, which occurs twice as often as each of the others, how much faster is P2 than P1?

1.6.6 [5] <1.4> At what frequency does P2 have the same performance as P1 for the instruction mix given in 1.6.5?

Exercise 1.7

The following table shows the increase in clock rate and power of eight generations of Intel processors over 28 years.

Processor	Clock Rate	Power
80286 (1982)	12.5 MHz	3.3 W
80386 (1985)	16 MHz	4.1 W
80486 (1989)	25 MHz	4.9 W
Pentium (1993)	66 MHz	10.1 W
Pentium Pro (1997)	200 MHz	29.1 W
Pentium 4 Willamette (2001)	2 GHz	75.3 W
Pentium 4 Prescott (2004)	3.6 GHz	103 W
Core 2 Kentsfield (2007)	2.667 GHz	95 W

1.7.1 [5] <1.5> What is the geometric mean of the ratios between consecutive generations for both clock rate and power? (The geometric mean is described in Section 1.7.)

1.7.2 [5] <1.5> What is the largest relative change in clock rate and power between generations?

1.7.3 [5] <1.5> How much larger is the clock rate and power of the last generation with respect to the first generation?

Consider the following values for voltage in each generation.

Processor	Voltage
80286 (1982)	5
80386 (1985)	5
80486 (1989)	5
Pentium (1993)	5
Pentium Pro (1997)	3.3
Pentium 4 Willamette (2001)	1.75
Pentium 4 Prescott (2004)	1.25
Core 2 Kentsfield (2007)	1.1

1.7.4 [5] <1.5> Find the average capacitive loads, assuming a negligible static power consumption.

1.7.5 [5] <1.5> Find the largest relative change in voltage between generations.

1.7.6 [5] <1.5> Find the geometric mean of the voltage ratios in the generations since the Pentium.

Exercise 1.8

Suppose we have developed new versions of a processor with the following characteristics.

	Version	Voltage	Clock rate
a.	version 1	1.75V	1.5GHz
	version 2	1.2V	2GHz
b.	version 1	1.1V	3GHz
	version 2	0.8V	4GHz

1.8.1 [5] <1.5> By how much has the capacitive load been reduced between versions if the dynamic power has been reduced by 10%?

1.8.2 [5] <1.5> By how much has the dynamic power been reduced if the capacitive load does not change?

1.8.3 [5] <1.5> Assuming that the capacitive load of version 2 is 80% the capacitive load of version 1, find the voltage for version 2 if the dynamic power of version 2 is reduced by 40% from version 1.

Supposing that the industry trends show that a new process generation scales as follows:

Capacitance	Voltage	Clock rate	Area
1	$1/2^{-1/4}$	$2^{1/2}$	$2^{-1/2}$

1.8.4 [5] <1.5> By what factor does the dynamic power scales?

1.8.5 [5] <1.5> Find the scaling of the capacitance per unit area.

1.8.6 [5] <1.5> Using data from Exercise 1.7, find the voltage and clock rate of the Core 2 processor for the next process generation.

Exercise 1.9

Although the dynamic power is the primary source of power dissipation in CMOS, leakage current produces a static power dissipation $V \times I_{\text{leak}}$. The smaller the on-chip dimensions, the more significant is the static power. Assume the figures shown in the following table for static and dynamic power dissipation for several generations of processors.

	Technology	Dynamic power (W)	Static power (W)	Voltage (V)
a.	250 nm	49	1	3.3
b.	90 nm	75	45	1.1

1.9.1 [5] <1.5> Find the percentage of the total dissipated power comprised by static power.

1.9.2 [5] <1.5> If the static power depends on the leakage current, $P_{\text{st}} = V \times I_{\text{leak}}$, find the leakage current for each technology.

1.9.3 [5] <1.5> Determine the ratio of static power to dynamic power for each technology.

Consider now the dynamic power dissipation of different versions of a given processor for three different voltages given in the following table.

	1.2 V	1.0 V	0.8 V
a.	80 W	70 W	40 W
b.	65 W	55 W	30 W

1.9.4 [5] <1.5> Determine the static power for each version at 0.8 V, assuming a static to dynamic power ratio of 0.6.

1.9.5 [5] <1.5> Find the leakage current for each version at 0.8 V.

1.9.6 [10] <1.5> Determine the larger of the two leakage currents at 1.0 V and 1.2 V, assuming a static to dynamic power ratio of 1.7.

Exercise 1.10

The table below shows the instruction type breakdown of a given application executed on 1, 2, 4, or 8 processors. Using this data, you will be exploring the speed-up of applications on parallel processors.

	Processors	# Instructions per processor			CPI		
		Arithmetic	Load/Store	Branch	Arithmetic	Load/Store	Branch
a.	1	2560	1280	256		1	4
	2	1280	640	128		1	4
	4	640	320	64		1	4
	8	320	160	32		1	4
b.	Processors	# Instructions per processor			CPI		
		Arithmetic	Load/Store	Branch	Arithmetic	Load/Store	Branch
	1	2560	1280	256		1	4
	2	1350	800	128		1	6
	4	800	600	64		1	9
	8	600	500	32		1	13

1.10.1 [5] <1.4, 1.6> The table above shows the number of instructions required per processor to complete a program on a multiprocessor with 1, 2, 4, or 8 processors. What is the total number of instructions executed per processor? What is the aggregate number of instructions executed across all processors?

1.10.2 [5] <1.4, 1.6> Given the CPI values on the right of the table above, find the total execution time for this program on 1, 2, 4, and 8 processors. Assume that each processor has a 2 GHz clock frequency.

1.10.3 [10] <1.4, 1.6> If the CPI of arithmetic instructions was doubled, what would the impact be on the execution time of the program on 1, 2, 4, or 8 processors?

The table below shows the number of instruction per processor core on a multicore processor as well as the average CPI for executing the program on 1, 2, 4, or 8 cores. Using this data, you will be exploring the speed-up of applications on multicore processors.

	Cores per processor	Instructions per core	Average CPI
a.	1	1.00E+10	1.2
	2	5.00E+09	1.3
	4	2.50E+09	1.5
	8	1.25E+09	1.8
	Cores per processor	Instructions per core	Average CPI
b.	1	1.00E+10	1.2
	2	5.00E+09	1.2
	4	2.50E+09	1.2
	8	1.25E+09	1.2

1.10.4 [10] <1.4, 1.6> Assuming a 3 GHz clock frequency, what is the execution time of the program using 1, 2, 4, or 8 cores.

1.10.5 [10] <1.5, 1.6> Assume that the power consumption of a processor core can be described by the following equation

$$\text{Power} = \frac{5.0\text{mA}}{\text{MHz}} \text{ Voltage}^2$$

where the operation voltage of the processor is described by the following equation

$$\text{Voltage} = \frac{1}{5} \text{ Frequency} + 0.4$$

with the frequency measured in GHz. So, at 5 GHz, the voltage would be 1.4 V. Find the power consumption of the program executing on 1, 2, 4, and 8 cores assuming that each core is operating at a 3 GHz clock frequency. Likewise, find the power consumption of the program executing on 1, 2, 4, or 8 cores assuming that each core is operating at 500 MHz.

1.10.6 [10] <1.5, 1.6> Find the energy required to execute the program for 1, 2, 4, and 8 cores assuming that each core has a clock frequency of 3 GHz and 500 MHz. Assume the power consumption equations from 1.10.5.

Exercise 1.11

The following table shows manufacturing data for various processors.

	Wafer diameter	Dies per wafer	Defects per unit area	cost per wafer
a.	15 cm	90	0.018 defects/cm ²	10
b.	25 cm	140	0.024 defects/cm ²	20

1.11.1 [10] <1.7> Find the yield.

1.11.2 [5] <1.7> Find the cost per die.

1.11.3 [10] <1.7> If the number of dies per wafer is increased by 10% and the defects per area unit increases by 15%, find the die area and yield.

Suppose that, with the evolution of the electronic devices manufacturing technology, the yield varies as shown in the following table.

	T1	T2	T3	T4
yield	0.85	0.89	0.92	0.95

1.11.4 [10] <1.7> Find the defects per area unit for each technology given a die area of 200 mm².

1.11.5 [5] <1.7> Represent graphically the variation of the yield together with the variation of defects per unit area.

Exercise 1.12

The following table shows results for SPEC2006 benchmark programs running on an AMD Barcelona.

	Name	Intr. count × 10 ⁹	Execution time (seconds)	Reference time (seconds)
a.	perl	2118	500	9770
b.	mcf 336		1200	9120

1.12.1 [5] <1.7> Find the CPI if the clock cycle time is 0.333 ns.

1.12.2 [5] <1.7> Find the SPEC ratio.

1.12.3 [5] <1.7> For these two benchmarks, find the geometric mean.

The following table shows data for further benchmarks.

	Name	CPI	Clock rate	SPECratio
a.	sjeng	0.96	4 GHz	14.5
b.	omnetpp	2.94	4 GHz	9.1

1.12.4 [5] <1.7> Find the increase in CPU time if the number of instruction of the benchmark is increased by 10% without affecting the CPI.

1.12.5 [5] <1.7> Find the increase in CPU time if the number of instruction of the benchmark is increased by 10% and the CPI is increased by 5%.

1.12.6 [5] <1.7> Find the change in the SPECratio for the change described in 1.12.5.

Exercise 1.13

Suppose that we are developing a new version of the AMD Barcelona processor with a 4 GHz clock rate. We have added some additional instructions to the instruction set in such a way that the number of instructions has been reduced by 15% from the values shown for each benchmark in Exercise 1.12. The execution times obtained are shown in the following table.

	Name	Execution time (seconds)	Reference time (seconds)	SPECratio
a.	perl	450	9770	21.7
b.	mcf	1150	9120	7.9

1.13.1 [10] <1.8> Find the new CPI.

1.13.2 [10] <1.8> In general, these CPI values are larger than those obtained in previous exercises for the same benchmarks. This is due mainly to the clock rate used in both cases, 3 GHz and 4 GHz. Determine whether the increase in the CPI is similar to that of the clock rate. If they are dissimilar, why?

1.13.3 [5] <1.8> By how much has the CPU time been reduced?

The following table shows data for further benchmarks.

	Name	Execution time (seconds)	CPI	Clock rate
a.	sjeng	820	0.96	3 GHz
b.	omnetpp	580	2.94	3 GHz

1.13.4 [10] <1.8> If the execution time is reduced by an additional 10% without affecting the CPI and with a clock rate of 4 GHz, determine the number of instructions.

1.13.5 [10] <1.8> Determine the clock rate required to give a further 10% reduction in CPU time while maintaining the number of instructions and CPI unchanged.

1.13.6 [10] <1.8> Determine the clock rate if the CPI is reduced by 15% and the CPU time by 20% while the number of instructions is unchanged.

Exercise 1.14

Section 1.8 cites as a pitfall the utilization of a subset of the performance equation as a performance metric. To illustrate this, consider the following data for the execution of given instruction sequence of 10^6 instructions in different processors.

Processor	Clock rate	CPI
P1	4 GHz	1.25
P2	3 GHz	0.75

1.14.1 [5] <1.8> One usual fallacy is to consider the computer with the largest clock rate as having the large performance. Check if this is true for P1 and P2.

1.14.2 [10] <1.8> Another fallacy is to consider that the processor executing the largest number of instruction will need a larger CPU time. Considering that processor P1 is executing a sequence of 10^6 instructions and that the CPI of processors P1 and P2 do not change, determine the number of instructions that P2 can execute in the same time that P1 needs to execute 10^6 instructions.

1.14.3 [10] <1.8> A common fallacy is to use MIPS (millions of instructions per second) to compare the performance of two different processors, and consider that the processor with the largest MIPS has the largest performance. Check if this is true for P1 and P2.

Another common performance figure is MFLOPS (million of floating-point operations per second), defined as

$$\text{MFLOPS} = \text{No. FP operations}/\text{execution time} \times 10^6$$

but this figure has the same problems as MIPS. Consider the programs in the following table, running on a processor with clock rate = 3 GHz.

	Instr. count	L/S instr.	FP instr.	Branch Instr.	CPI(L/S)	CPI(FP)	CPI(Branch)
a.	10^6	50%	40%	10%	0.75	1	1.5
b.	3×10^6	40%	40%	20%	1.25	0.70	1.25

1.14.4 [10] <1.8> Find the MFLOPS figures for the programs.

1.14.5 [10] <1.8> Find the MIPS figures for the programs.

1.14.6 [10] <1.8> Find the performance for the programs and compare with MIPS and MFLOPS.

Exercise 1.15

Another pitfall cited in Section 1.8 is expecting to improve the overall performance of a computer by improving only one aspect of the computer. This might be true, but not always. Consider a computer running programs with CPU times shown in the following table.

	FP instr.	INT instr.	L/S instr.	Branch instr.	Total time
a.	35 s	85 s	50 s	30 s	200 s
b.	50 s	80 s	50 s	30 s	210 s

1.15.1 [5] <1.8> By how much is the total time reduced if the time for FP operations is reduced by 20%?

1.15.2 [5] <1.8> By how much is the time for INT operations reduced if the total time is reduced by 20%?

1.15.3 [5] <1.8> Can the total time can be reduced by 20% by reducing only the time for branch instructions?

The following table shows the instruction type breakdown per processor of a given application executed in different numbers of processors.

	# Processors	FP instr.	INT instr.	L/S instr.	Branch Instr.	CPI (FP)	CPI (INT)	CPI (L/S)	CPI (Branch)
a.	1	560×10^6	2000×10^6	1280×10^6	256×10^6	1	1	4	2
b.	8	80×10^6	240×10^6	160×10^6	32×10^6	1	1	4	2

Assume that each processor has a 2 GHz clock rate.

1.15.4 [10] <1.8> By how much must we improve the CPI of FP instructions if we want the program to run two times faster?

1.15.5 [10] <1.8> By how much must we improve the CPI of L/S instructions if we want the program to run two times faster?

1.15.6 [5] <1.8> By how much is the execution time of the program improved if the CPI of INT and FP instructions is reduced by 40% and the CPI of L/S and branch is reduced by 30%?

Exercise 1.16

Another pitfall, relating to the execution of programs in multiprocessor systems, is expecting improvement in performance by improving only the execution time of part of the routines. The following table shows the execution time of five routines of a program running on different numbers of processors.

	# Processors	Routine A (ms)	Routine B (ms)	Routine C (ms)	Routine D (ms)	Routine E (ms)
a.	2	20	80	10	70	5
b.	16	4	14	2	12	2

1.16.1 [10] <1.8> Find the total execution time and by how much it is reduced if the time of routines A, C, and E is improved by 15%.

1.16.2 [10] <1.8> By how much is the total time reduced if routine B is improved by 10%?

1.16.3 [10] <1.8> By how much is the total time reduced if routine D is improved by 10%?

Execution time in a multiprocessor system can be split into computing time for the routines plus routing time spent sending data from one processor to another. Consider the execution time and routing time given in the following table. In this case, the routing time is an important component of the total time.

# Processors	Routine A (ms)	Routine B (ms)	Routine C (ms)	Routine D (ms)	Routine E (ms)	Routing (ms)
2	20	78 9 65	4 11			
4	12	44 4 34	2 13			
8	1 23 3	19 3 17				
16	4 13 1	10 2 22				
32	2 5 15	1				23
64	1	3 0 5 1			1	26

1.16.4 [10] <1.8> For each doubling of the number of processors, determine the ratio of new to old computing time and the ratio of new to old routing time.

1.16.5 [5] <1.8> Using the geometric means of the ratios, extrapolate to find the computing time and routing time in a 128-processor system.

1.16.6 [10] <1.8> Find the computing time and routing time for a system with one processor.

§1.1, page 9: Discussion questions: many answers are acceptable.

§1.3, page 25: Disk memory: nonvolatile, long access time (milliseconds), and cost \$0.20–\$2.00/GB. Semiconductor memory: volatile, short access time (nanoseconds), and cost \$20–\$75/GB.

§1.4, page 31: 1. a: both, b: latency, c: neither. 2. 7 seconds.

§1.4, page 38: b.

§1.7, page 50: 1, 3, and 4 are valid reasons. Answer 5 can be generally true because high volume can make the extra investment to reduce die size by, say, 10% a good economic decision, but it doesn't have to be true.

§1.8, page 53: a. Computer A has the higher MIPS rating. b. Computer B is faster.

Answers to Check Yourself

2



*I speak Spanish
to God, Italian to
women, French to
men, and German to
my horse.*

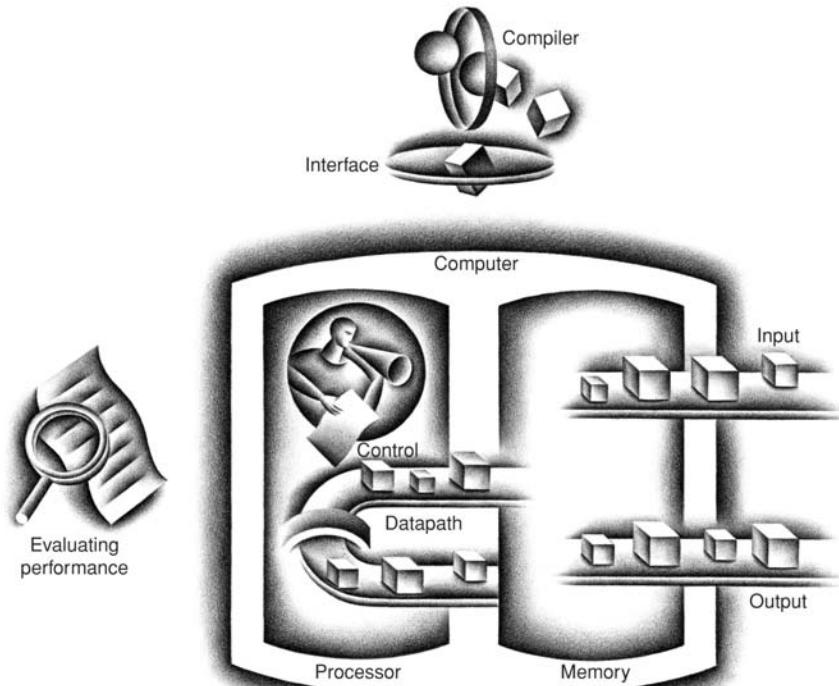
Charles V, King of France
1337–1380

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The Five Classic Components of a Computer



instruction set The vocabulary of commands understood by a given architecture.

2.1

Introduction

To command a computer's hardware, you must speak its language. The words of a computer's language are called *instructions*, and its vocabulary is called an **instruction set**. In this chapter, you will see the instruction set of a real computer, both in the form written by people and in the form read by the computer. We introduce instructions in a top-down fashion. Starting from a notation that looks like a restricted programming language, we refine it step-by-step until you see the real language of a real computer. Chapter 3 continues our downward descent, unveiling the hardware for arithmetic and the representation of floating-point numbers.

You might think that the languages of computers would be as diverse as those of people, but in reality computer languages are quite similar, more like regional dialects than like independent languages. Hence, once you learn one, it is easy to pick up others. This similarity occurs because all computers are constructed from hardware technologies based on similar underlying principles and because there are a few basic operations that all computers must provide. Moreover, computer designers have a common goal: to find a language that makes it easy to build the hardware and the compiler while maximizing performance and minimizing cost and power. This goal is time honored; the following quote was written before you could buy a computer, and it is as true today as it was in 1947:

It is easy to see by formal-logical methods that there exist certain [instruction sets] that are in abstract adequate to control and cause the execution of any sequence of operations The really decisive considerations from the present point of view, in selecting an [instruction set], are more of a practical nature: simplicity of the equipment demanded by the [instruction set], and the clarity of its application to the actually important problems together with the speed of its handling of those problems.

Burks, Goldstine, and von Neumann, 1947

The “simplicity of the equipment” is as valuable a consideration for today’s computers as it was for those of the 1950s. The goal of this chapter is to teach an instruction set that follows this advice, showing both how it is represented in hardware and the relationship between high-level programming languages and this more primitive one. Our examples are in the C programming language;  [Section 2.15](#) on the CD shows how these would change for an object-oriented language like Java.

By learning how to represent instructions, you will also discover the secret of computing: the **stored-program concept**. Moreover, you will exercise your “foreign language” skills by writing programs in the language of the computer and running them on the simulator that comes with this book. You will also see the impact of programming languages and compiler optimization on performance. We conclude with a look at the historical evolution of instruction sets and an overview of other computer dialects.

The chosen instruction set comes from MIPS Technologies, which is an elegant example of the instruction sets designed since the 1980s. Later, we will take a quick look at two other popular instruction sets. ARM is quite similar to MIPS, and more than three billion ARM processors were shipped in embedded devices in 2008. The other example, the Intel x86, is inside almost all of the 330 million PCs made in 2008.

We reveal the MIPS instruction set a piece at a time, giving the rationale along with the computer structures. This top-down, step-by-step tutorial weaves the components with their explanations, making the computer’s language more palatable. Figure 2.1 gives a sneak preview of the instruction set covered in this chapter.

stored-program concept The idea that instructions and data of many types can be stored in memory as numbers, leading to the stored-program computer.

2.2

Operations of the Computer Hardware

Every computer must be able to perform arithmetic. The MIPS assembly language notation

```
add a, b, c
```

instructs a computer to add the two variables *b* and *c* and to put their sum in *a*.

This notation is rigid in that each MIPS arithmetic instruction performs only one operation and must always have exactly three variables. For example, suppose we want to place the sum of four variables *b*, *c*, *d*, and *e* into variable *a*. (In this section we are being deliberately vague about what a “variable” is; in the next section we’ll explain in detail.)

The following sequence of instructions adds the four variables:

```
add a, b, c      # The sum of b and c is placed in a.  
add a, a, d      # The sum of b, c, and d is now in a.  
add a, a, e      # The sum of b, c, d, and e is now in a.
```

Thus, it takes three instructions to sum the four variables.

The words to the right of the sharp symbol (#) on each line above are *comments* for the human reader, and the computer ignores them. Note that unlike other programming languages, each line of this language can contain at most one instruction. Another difference from C is that comments always terminate at the end of a line.

There must certainly be instructions for performing the fundamental arithmetic operations.

Burks, Goldstine, and von Neumann, 1947

MIPS operands

Name	Example	Comments
32 registers	<code>\$s0-\$s7, \$t0-\$t9, \$zero, \$a0-\$a3, \$v0-\$v1, \$gp, \$fp, \$sp, \$ra, \$at</code>	Fast locations for data. In MIPS, data must be in register <code>s</code> to perform arithmetic, register <code>\$zero</code> always equals 0, and register <code>\$at</code> is reserved by the assembler to handle large constants.
2^{30} memory words	<code>Memory[0], Memory[4], ..., Memory[4294967292]</code>	Accessed only by data transfer instructions. MIPS uses byte addresses, so sequential word addresses differ by 4. Memory holds data structures, arrays, and spilled registers.

MIPS assembly language

Category	Instruction	Example	Meaning	Comments
Arithmetic	add	<code>add \$s1,\$s2,\$s3</code>	$\$s1 = \$s2 + \$s3$	Three register operands
	subtract	<code>sub \$s1,\$s2,\$s3</code>	$\$s1 = \$s2 - \$s3$	Three register operands
	add immediate	<code>addi \$s1,\$s2,20</code>	$\$s1 = \$s2 + 20$	Used to add constants
Data transfer	load word	<code>lw \$s1,20(\$s2)</code>	$\$s1 = \text{Memory}[\$s2 + 20]$	Word from memory to register
	store word	<code>sw \$s1,20(\$s2)</code>	$\text{Memory}[\$s2 + 20] = \$s1$	Word from register to memory
	load half	<code>lh \$s1,20(\$s2)</code>	$\$s1 = \text{Memory}[\$s2 + 20]$	Halfword memory to register
	load half unsigned	<code>lhu \$s1,20(\$s2)</code>	$\$s1 = \text{Memory}[\$s2 + 20]$	Halfword memory to register
	store half	<code>sh \$s1,20(\$s2)</code>	$\text{Memory}[\$s2 + 20] = \$s1$	Halfword register to memory
	load byte	<code>lb \$s1,20(\$s2)</code>	$\$s1 = \text{Memory}[\$s2 + 20]$	Byte from memory to register
	load byte unsigned	<code>lbu \$s1,20(\$s2)</code>	$\$s1 = \text{Memory}[\$s2 + 20]$	Byte from memory to register
	store byte	<code>sb \$s1,20(\$s2)</code>	$\text{Memory}[\$s2 + 20] = \$s1$	Byte from register to memory
	load linked word	<code>l1 \$s1,20(\$s2)</code>	$\$s1 = \text{Memory}[\$s2 + 20]$	Load word as 1st half of atomic swap
	store condition. word	<code>sc \$s1,20(\$s2)</code>	$\text{Memory}[\$s2+20]=\$s1; \$s1=0 \text{ or } 1$	Store word as 2nd half of atomic swap
Logical	load upper immed.	<code>lui \$s1,20</code>	$\$s1 = 20 * 2^{16}$	Loads constant in upper 16 bits
	and	<code>and \$s1,\$s2,\$s3</code>	$\$s1 = \$s2 \& \$s3$	Three reg. operands; bit-by-bit AND
	or	<code>or \$s1,\$s2,\$s3</code>	$\$s1 = \$s2 \$s3$	Three reg. operands; bit-by-bit OR
	nor	<code>nor \$s1,\$s2,\$s3</code>	$\$s1 = \sim (\$s2 \$s3)$	Three reg. operands; bit-by-bit NOR
	and immediate	<code>andi \$s1,\$s2,20</code>	$\$s1 = \$s2 \& 20$	Bit-by-bit AND reg with constant
	or immediate	<code>ori \$s1,\$s2,20</code>	$\$s1 = \$s2 20$	Bit-by-bit OR reg with constant
	shift left logical	<code>sll \$s1,\$s2,10</code>	$\$s1 = \$s2 << 10$	Shift left by constant
Conditional branch	shift right logical	<code>srl \$s1,\$s2,10</code>	$\$s1 = \$s2 >> 10$	Shift right by constant
	branch on equal	<code>beq \$s1,\$s2,25</code>	if ($\$s1 == \$s2$) go to PC + 4 + 100	Equal test; PC-relative branch
	branch on not equal	<code>bne \$s1,\$s2,25</code>	if ($\$s1 != \$s2$) go to PC + 4 + 100	Not equal test; PC-relative
	set on less than	<code>slt \$s1,\$s2,\$s3</code>	if ($\$s2 < \$s3$) $\$s1 = 1$; else $\$s1 = 0$	Compare less than; for beq, bne
	set on less than unsigned	<code>sltu \$s1,\$s2,\$s3</code>	if ($\$s2 < \$s3$) $\$s1 = 1$; else $\$s1 = 0$	Compare less than unsigned
	set less than immediate	<code>slti \$s1,\$s2,20</code>	if ($\$s2 < 20$) $\$s1 = 1$; else $\$s1 = 0$	Compare less than constant
Unconditional jump	set less than immediate unsigned	<code>sltiu \$s1,\$s2,20</code>	if ($\$s2 < 20$) $\$s1 = 1$; else $\$s1 = 0$	Compare less than constant unsigned
	jump	<code>j 2500</code>	go to 10000	Jump to target address
	jump register	<code>jr \$ra</code>	go to <code>\$ra</code>	For switch, procedure return
	jump and link	<code>jal 2500</code>	$\$ra = \text{PC} + 4$; go to 10000	For procedure call

FIGURE 2.1 MIPS assembly language revealed in this chapter. This information is also found in Column 1 of the MIPS Reference Data Card at the front of this book.

The natural number of operands for an operation like addition is three: the two numbers being added together and a place to put the sum. Requiring every instruction to have exactly three operands, no more and no less, conforms to the philosophy of keeping the hardware simple: hardware for a variable number of operands is more complicated than hardware for a fixed number. This situation illustrates the first of four underlying principles of hardware design:

Design Principle 1: Simplicity favors regularity.

We can now show, in the two examples that follow, the relationship of programs written in higher-level programming languages to programs in this more primitive notation.

Compiling Two C Assignment Statements into MIPS

This segment of a C program contains the five variables a, b, c, d, and e. Since Java evolved from C, this example and the next few work for either high-level programming language:

```
a = b + c;  
d = a - e;
```

The translation from C to MIPS assembly language instructions is performed by the *compiler*. Show the MIPS code produced by a compiler.

A MIPS instruction operates on two source operands and places the result in one destination operand. Hence, the two simple statements above compile directly into these two MIPS assembly language instructions:

```
add a, b, c  
sub d, a, e
```

EXAMPLE**ANSWER**

Compiling a Complex C Assignment into MIPS

A somewhat complex statement contains the five variables f, g, h, i, and j:

```
f = (g + h) - (i + j);
```

What might a C compiler produce?

EXAMPLE

ANSWER

The compiler must break this statement into several assembly instructions, since only one operation is performed per MIPS instruction. The first MIPS instruction calculates the sum of *g* and *h*. We must place the result somewhere, so the compiler creates a temporary variable, called *t0*:

```
add t0,g,h # temporary variable t0 contains g + h
```

Although the next operation is subtract, we need to calculate the sum of *i* and *j* before we can subtract. Thus, the second instruction places the sum of *i* and *j* in another temporary variable created by the compiler, called *t1*:

```
add t1,i,j # temporary variable t1 contains i + j
```

Finally, the subtract instruction subtracts the second sum from the first and places the difference in the variable *f*, completing the compiled code:

```
sub f,t0,t1 # f gets t0 - t1, which is (g + h) - (i + j)
```

Check Yourself

For a given function, which programming language likely takes the most lines of code? Put the three representations below in order.

1. Java
2. C
3. MIPS assembly language

Elaboration: To increase portability, Java was originally envisioned as relying on a software interpreter. The instruction set of this interpreter is called *Java bytecodes* (see  [Section 2.15](#) on the CD), which is quite different from the MIPS instruction set. To get performance close to the equivalent C program, Java systems today typically compile Java bytecodes into the native instruction sets like MIPS. Because this compilation is normally done much later than for C programs, such Java compilers are often called *Just In Time (JIT) compilers*. [Section 2.12](#) shows how JITs are used later than C compilers in the start-up process, and [Section 2.13](#) shows the performance consequences of compiling versus interpreting Java programs.

2.3**Operands of the Computer Hardware**

Unlike programs in high-level languages, the operands of arithmetic instructions are restricted; they must be from a limited number of special locations built directly in hardware called *registers*. Registers are primitives used in hardware design that

are also visible to the programmer when the computer is completed, so you can think of registers as the bricks of computer construction. The size of a register in the MIPS architecture is 32 bits; groups of 32 bits occur so frequently that they are given the name **word** in the MIPS architecture.

One major difference between the variables of a programming language and registers is the limited number of registers, typically 32 on current computers, like MIPS. (See  [Section 2.20](#) on the CD for the history of the number of registers.) Thus, continuing in our top-down, stepwise evolution of the symbolic representation of the MIPS language, in this section we have added the restriction that the three operands of MIPS arithmetic instructions must each be chosen from one of the 32 32-bit registers.

The reason for the limit of 32 registers may be found in the second of our four underlying design principles of hardware technology:

Design Principle 2: Smaller is faster.

A very large number of registers may increase the clock cycle time simply because it takes electronic signals longer when they must travel farther.

Guidelines such as “smaller is faster” are not absolutes; 31 registers may not be faster than 32. Yet, the truth behind such observations causes computer designers to take them seriously. In this case, the designer must balance the craving of programs for more registers with the designer’s desire to keep the clock cycle fast. Another reason for not using more than 32 is the number of bits it would take in the instruction format, as [Section 2.5](#) demonstrates.

Chapter 4 shows the central role that registers play in hardware construction; as we shall see in this chapter, effective use of registers is critical to program performance.

Although we could simply write instructions using numbers for registers, from 0 to 31, the MIPS convention is to use two-character names following a dollar sign to represent a register. [Section 2.8](#) will explain the reasons behind these names. For now, we will use `$s0, $s1, ...` for registers that correspond to variables in C and Java programs and `$t0, $t1, ...` for temporary registers needed to compile the program into MIPS instructions.

word The natural unit of access in a computer, usually a group of 32 bits; corresponds to the size of a register in the MIPS architecture.

Compiling a C Assignment Using Registers

It is the compiler’s job to associate program variables with registers. Take, for instance, the assignment statement from our earlier example:

`f = (g + h) - (i + j);`

EXAMPLE

The variables `f, g, h, i,` and `j` are assigned to the registers `$s0, $s1, $s2, $s3,` and `$s4`, respectively. What is the compiled MIPS code?

ANSWER

The compiled program is very similar to the prior example, except we replace the variables with the register names mentioned above plus two temporary registers, \$t0 and \$t1, which correspond to the temporary variables above:

```
add $t0,$s1,$s2 # register $t0 contains g + h
add $t1,$s3,$s4 # register $t1 contains i + j
sub $s0,$t0,$t1 # f gets $t0 - $t1, which is (g + h)-(i + j)
```

Memory Operands

Programming languages have simple variables that contain single data elements, as in these examples, but they also have more complex data structures—arrays and structures. These complex data structures can contain many more data elements than there are registers in a computer. How can a computer represent and access such large structures?

Recall the five components of a computer introduced in Chapter 1 and repeated on page 75. The processor can keep only a small amount of data in registers, but computer memory contains billions of data elements. Hence, data structures (arrays and structures) are kept in memory.

As explained above, arithmetic operations occur only on registers in MIPS instructions; thus, MIPS must include instructions that transfer data between memory and registers. Such instructions are called **data transfer instructions**. To access a word in memory, the instruction must supply the memory **address**. Memory is just a large, single-dimensional array, with the address acting as the index to that array, starting at 0. For example, in Figure 2.2, the address of the third data element is 2, and the value of Memory[2] is 10.

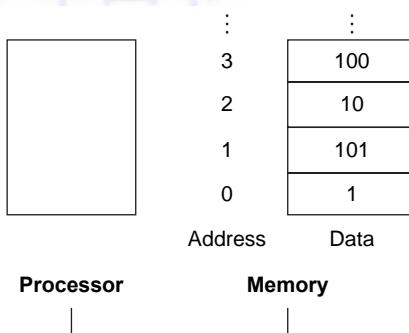


FIGURE 2.2 Memory addresses and contents of memory at those locations. If these elements were words, these addresses would be incorrect, since MIPS actually uses byte addressing, with each word representing four bytes. Figure 2.3 shows the memory addressing for sequential word addresses.

The data transfer instruction that copies data from memory to a register is traditionally called *load*. The format of the load instruction is the name of the operation followed by the register to be loaded, then a constant and register used to access memory. The sum of the constant portion of the instruction and the contents of the second register forms the memory address. The actual MIPS name for this instruction is `lw`, standing for *load word*.

Compiling an Assignment When an Operand Is in Memory

Let's assume that `A` is an array of 100 words and that the compiler has associated the variables `g` and `h` with the registers `$s1` and `$s2` as before. Let's also assume that the starting address, or *base address*, of the array is in `$s3`. Compile this C assignment statement:

```
g = h + A[8];
```

Although there is a single operation in this assignment statement, one of the operands is in memory, so we must first transfer `A[8]` to a register. The address of this array element is the sum of the base of the array `A`, found in register `$s3`, plus the number to select element 8. The data should be placed in a temporary register for use in the next instruction. Based on Figure 2.2, the first compiled instruction is

```
lw    $t0,8($s3) # Temporary reg $t0 gets A[8]
```

(On the next page we'll make a slight adjustment to this instruction, but we'll use this simplified version for now.) The following instruction can operate on the value in `$t0` (which equals `A[8]`) since it is in a register. The instruction must add `h` (contained in `$s2`) to `A[8]` (`$t0`) and put the sum in the register corresponding to `g` (associated with `$s1`):

```
add  $s1,$s2,$t0 # g = h + A[8]
```

The constant in a data transfer instruction (8) is called the *offset*, and the register added to form the address (`$s3`) is called the *base register*.

EXAMPLE

ANSWER

Hardware/ Software Interface

alignment restriction
 A requirement that data be aligned in memory on natural boundaries.

In addition to associating variables with registers, the compiler allocates data structures like arrays and structures to locations in memory. The compiler can then place the proper starting address into the data transfer instructions.

Since 8-bit *bytes* are useful in many programs, most architectures address individual bytes. Therefore, the address of a word matches the address of one of the 4 bytes within the word, and addresses of sequential words differ by 4. For example, Figure 2.3 shows the actual MIPS addresses for the words in Figure 2.2; the byte address of the third word is 8.

In MIPS, words must start at addresses that are multiples of 4. This requirement is called an **alignment restriction**, and many architectures have it. (Chapter 4 suggests why alignment leads to faster data transfers.)

Computers divide into those that use the address of the leftmost or “big end” byte as the word address versus those that use the rightmost or “little end” byte. MIPS is in the *big-endian* camp. (Appendix B, shows the two options to number bytes in a word.)

Byte addressing also affects the array index. To get the proper byte address in the code above, *the offset to be added to the base register \$s3 must be 4×8 , or 32*, so that the load address will select A[8] and not A[8/4]. (See the related pitfall on page 175 of Section 2.18.)

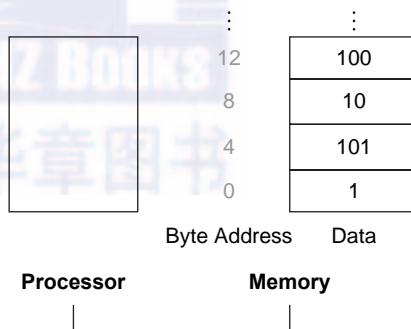


FIGURE 2.3 Actual MIPS memory addresses and contents of memory for those words.
 The changed addresses are highlighted to contrast with Figure 2.2. Since MIPS addresses each byte, word addresses are multiples of 4: there are 4 bytes in a word.

The instruction complementary to load is traditionally called *store*; it copies data from a register to memory. The format of a store is similar to that of a load: the name of the operation, followed by the register to be stored, then offset to select the array element, and finally the base register. Once again, the MIPS address is specified in part by a constant and in part by the contents of a register. The actual MIPS name is `sw`, standing for *store word*.

Compiling Using Load and Store

Assume variable `h` is associated with register `$s2` and the base address of the array `A` is in `$s3`. What is the MIPS assembly code for the C assignment statement below?

```
A[12] = h + A[8];
```

EXAMPLE

Although there is a single operation in the C statement, now two of the operands are in memory, so we need even more MIPS instructions. The first two instructions are the same as the prior example, except this time we use the proper offset for byte addressing in the load word instruction to select `A[8]`, and the add instruction places the sum in `$t0`:

```
lw    $t0,32($s3)  # Temporary reg $t0 gets A[8]
add  $t0,$s2,$t0  # Temporary reg $t0 gets h + A[8]
```

The final instruction stores the sum into `A[12]`, using 48 (4×12) as the offset and register `$s3` as the base register.

```
sw    $t0,48($s3)  # Stores h + A[8] back into A[12]
```

ANSWER

Load word and store word are the instructions that copy words between memory and registers in the MIPS architecture. Other brands of computers use other instructions along with load and store to transfer data. An architecture with such alternatives is the Intel x86, described in Section 2.17.

Hardware/ Software Interface

Many programs have more variables than computers have registers. Consequently, the compiler tries to keep the most frequently used variables in registers and places the rest in memory, using loads and stores to move variables between registers and memory. The process of putting less commonly used variables (or those needed later) into memory is called *spilling* registers.

The hardware principle relating size and speed suggests that memory must be slower than registers, since there are fewer registers. This is indeed the case; data accesses are faster if data is in registers instead of memory.

Moreover, data is more useful when in a register. A MIPS arithmetic instruction can read two registers, operate on them, and write the result. A MIPS data transfer instruction only reads one operand or writes one operand, without operating on it.

Thus, registers take less time to access *and* have higher throughput than memory, making data in registers both faster to access and simpler to use. Accessing registers also uses less energy than accessing memory. To achieve highest performance and conserve energy, compilers must use registers efficiently.

Constant or Immediate Operands

Many times a program will use a constant in an operation—for example, incrementing an index to point to the next element of an array. In fact, more than half of the MIPS arithmetic instructions have a constant as an operand when running the SPEC2006 benchmarks.

Using only the instructions we have seen so far, we would have to load a constant from memory to use one. (The constants would have been placed in memory when the program was loaded.) For example, to add the constant 4 to register \$s3, we could use the code

```
lw $t0, AddrConstant4($s1)    # $t0 = constant 4
add $s3,$s3,$t0                # $s3 = $s3 + $t0 ($t0 == 4)
```

assuming that \$s1 + AddrConstant4 is the memory address of the constant 4.

An alternative that avoids the load instruction is to offer versions of the arithmetic instructions in which one operand is a constant. This quick add instruction with one constant operand is called *add immediate* or *addi*. To add 4 to register \$s3, we just write

```
addi    $s3,$s3,4           # $s3 = $s3 + 4
```

Immediate instructions illustrate the third hardware design principle, first mentioned in the Fallacies and Pitfalls of Chapter 1:

Design Principle 3: Make the common case fast.

Constant operands occur frequently, and by including constants inside arithmetic instructions, operations are much faster and use less energy than if constants were loaded from memory.

The constant zero has another role, which is to simplify the instruction set by offering useful variations. For example, the move operation is just an add instruction where one operand is zero. Hence, MIPS dedicates a register \$zero to be hard-wired to the value zero. (As you might expect, it is register number 0.)

Given the importance of registers, what is the rate of increase in the number of registers in a chip over time?

Check Yourself

1. Very fast: They increase as fast as Moore's law, which predicts doubling the number of transistors on a chip every 18 months.
2. Very slow: Since programs are usually distributed in the language of the computer, there is inertia in instruction set architecture, and so the number of registers increases only as fast as new instruction sets become viable.

Elaboration: Although the MIPS register s in this book are 32 bits wide, there is a 64-bit version of the MIPS instruction set with 32 64-bit register s. To keep them straight, they are officially called MIPS-32 and MIPS-64. In this chapter, we use a subset of MIPS-32.  Appendix E shows the differences between MIPS-32 and MIPS-64.

The MIPS offset plus base register addressing is an excellent match to structures as well as arrays, since the register can point to the beginning of the structure and the offset can select the desired element. We'll see such an example in Section 2.13.

The register in the data transfer instructions was originally invented to hold an index of an array with the offset used for the starting address of an array. Thus, the base register is also called the *index register*. Today's memories are much larger and the software model of data allocation is more sophisticated, so the base address of the array is normally passed in a register since it won't fit in the offset, as we shall see.

Since MIPS supports negative constants, there is no need for subtract immediate in MIPS.

2.4

Signed and Unsigned Numbers

First, let's quickly review how a computer represents numbers. Humans are taught to think in base 10, but numbers may be represented in any base. For example, 123 base 10 = 1111011 base 2.

Numbers are kept in computer hardware as a series of high and low electronic signals, and so they are considered base 2 numbers. (Just as base 10 numbers are called *decimal* numbers, base 2 numbers are called *binary* numbers.)

A single digit of a binary number is thus the "atom" of computing, since all information is composed of binary digits or *bits*. This fundamental building block

binary digit Also called **binary bit**. One of the two numbers in base 2, 0 or 1, that are the components of information.

can be one of two values, which can be thought of as several alternatives: high or low, on or off, true or false, or 1 or 0.

Generalizing the point, in any number base, the value of i th digit d is

$$d \times \text{Base}^i$$

where i starts at 0 and increases from right to left. This leads to an obvious way to number the bits in the word: simply use the power of the base for that bit. We subscript decimal numbers with *ten* and binary numbers with *two*. For example,

1011_{two}

represents

$$\begin{aligned} & (1 \times 2^3) + (0 \times 2^2) + (1 \times 2^1) + (1 \times 2^0)_{\text{ten}} \\ & = (1 \times 8) + (0 \times 4) + (1 \times 2) + (1 \times 1)_{\text{ten}} \\ & = 8 + 0 + 2 + 1_{\text{ten}} \\ & = 11_{\text{ten}} \end{aligned}$$

We number the bits 0, 1, 2, 3, . . . from *right to left* in a word. The drawing below shows the numbering of bits within a MIPS word and the placement of the number 1011_{two} :

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1

(32 bits wide)

Since words are drawn vertically as well as horizontally, leftmost and rightmost may be unclear. Hence, the phrase **least significant bit** is used to refer to the rightmost bit (bit 0 above) and **most significant bit** to the leftmost bit (bit 31).

The MIPS word is 32 bits long, so we can represent 2^{32} different 32-bit patterns. It is natural to let these combinations represent the numbers from 0 to $2^{32} - 1$ ($4,294,967,295_{\text{ten}}$):

$$\begin{aligned} 0000 & 0000 0000 0000 0000 0000 0000 0000_{\text{two}} = 0_{\text{ten}} \\ 0000 & 0000 0000 0000 0000 0000 0001_{\text{two}} = 1_{\text{ten}} \\ 0000 & 0000 0000 0000 0000 0000 0010_{\text{two}} = 2_{\text{ten}} \\ \dots & \quad \quad \quad \dots \\ 1111 & 1111 1111 1111 1111 1111 1111 1101_{\text{two}} = 4,294,967,293_{\text{ten}} \\ 1111 & 1111 1111 1111 1111 1111 1111 1110_{\text{two}} = 4,294,967,294_{\text{ten}} \\ 1111 & 1111 1111 1111 1111 1111 1111 1111_{\text{two}} = 4,294,967,295_{\text{ten}} \end{aligned}$$

That is, 32-bit binary numbers can be represented in terms of the bit value times a power of 2 (here x_i means the i th bit of x):

least significant bit
The rightmost bit in a MIPS word.

most significant bit
The leftmost bit in a MIPS word.

$$(x_{31} \times 2^{31}) + (x_{30} \times 2^{30}) + (x_{29} \times 2^{29}) + \dots + (x_1 \times 2^1) + (x_0 \times 2^0)$$

Keep in mind that the binary bit patterns above are simply *representatives* of numbers. Numbers really have an infinite number of digits, with almost all being 0 except for a few of the rightmost digits. We just don't normally show leading 0s.

Hardware can be designed to add, subtract, multiply, and divide these binary bit patterns. If the number that is the proper result of such operations cannot be represented by these rightmost hardware bits, *overflow* is said to have occurred. It's up to the programming language, the operating system, and the program to determine what to do if overflow occurs.

Computer programs calculate both positive and negative numbers, so we need a representation that distinguishes the positive from the negative. The most obvious solution is to add a separate sign, which conveniently can be represented in a single bit; the name for this representation is *sign and magnitude*.

Alas, sign and magnitude representation has several shortcomings. First, it's not obvious where to put the sign bit. To the right? To the left? Early computers tried both. Second, adders for sign and magnitude may need an extra step to set the sign because we can't know in advance what the proper sign will be. Finally, a separate sign bit means that sign and magnitude has both a positive and a negative zero, which can lead to problems for inattentive programmers. As a result of these shortcomings, sign and magnitude representation was soon abandoned.

In the search for a more attractive alternative, the question arose as to what would be the result for unsigned numbers if we tried to subtract a large number from a small one. The answer is that it would try to borrow from a string of leading 0s, so the result would have a string of leading 1s.

Given that there was no obvious better alternative, the final solution was to pick the representation that made the hardware simple: leading 0s mean positive, and leading 1s mean negative. This convention for representing signed binary numbers is called *two's complement* representation:

0000 0000 0000 0000 0000 0000 0000 _{two}	= 0 _{ten}
0000 0000 0000 0000 0000 0000 0001 _{two}	= 1 _{ten}
0000 0000 0000 0000 0000 0000 0010 _{two}	= 2 _{ten}
...	...
0111 1111 1111 1111 1111 1111 1101 _{two}	= 2,147,483,645 _{ten}
0111 1111 1111 1111 1111 1111 1110 _{two}	= 2,147,483,646 _{ten}
0111 1111 1111 1111 1111 1111 1111 _{two}	= 2,147,483,647 _{ten}
1000 0000 0000 0000 0000 0000 0000 _{two}	= -2,147,483,648 _{ten}
1000 0000 0000 0000 0000 0000 0001 _{two}	= -2,147,483,647 _{ten}
1000 0000 0000 0000 0000 0000 0010 _{two}	= -2,147,483,646 _{ten}
...	...
1111 1111 1111 1111 1111 1111 1101 _{two}	= -3 _{ten}
1111 1111 1111 1111 1111 1111 1110 _{two}	= -2 _{ten}
1111 1111 1111 1111 1111 1111 1111 _{two}	= -1 _{ten}

The positive half of the numbers, from 0 to $2,147,483,647_{\text{ten}}$ ($2^{31} - 1$), use the same representation as before. The following bit pattern (1000 ... 0000_{two}) represents the most negative number $-2,147,483,648_{\text{ten}}$ (-2^{31}). It is followed by a declining set of negative numbers: $-2,147,483,647_{\text{ten}}$ (1000 ... 0001_{two}) down to -1_{ten} (1111 ... 1111_{two}).

Two's complement does have one negative number, $-2,147,483,648_{\text{ten}}$, that has no corresponding positive number. Such imbalance was also a worry to the inattentive programmer, but sign and magnitude had problems for both the programmer *and* the hardware designer. Consequently, every computer today uses two's complement binary representations for signed numbers.

Two's complement representation has the advantage that all negative numbers have a 1 in the most significant bit. Consequently, hardware needs to test only this bit to see if a number is positive or negative (with the number 0 considered positive). This bit is often called the *sign bit*. By recognizing the role of the sign bit, we can represent positive and negative 32-bit numbers in terms of the bit value times a power of 2:

$$(x31 \times -2^{31}) + (x30 \times 2^{30}) + (x29 \times 2^{29}) + \dots + (x1 \times 2^1) + (x0 \times 2^0)$$

The sign bit is multiplied by -2^{31} , and the rest of the bits are then multiplied by positive versions of their respective base values.

EXAMPLE

Binary to Decimal Conversion

What is the decimal value of this 32-bit two's complement number?

1111 1111 1111 1111 1111 1111 1111 1100_{two}

ANSWER

Substituting the number's bit values into the formula above:

$$\begin{aligned} & (1 \times -2^{31}) + (1 \times 2^{30}) + (1 \times 2^{29}) + \dots + (1 \times 2^2) + (0 \times 2^1) + (0 \times 2^0) \\ &= -2^{31} + 2^{30} + 2^{29} + \dots + 2^2 + 0 + 0 \\ &= -2,147,483,648_{\text{ten}} + 2,147,483,644_{\text{ten}} \\ &= -4_{\text{ten}} \end{aligned}$$

We'll see a shortcut to simplify conversion from negative to positive soon.

Just as an operation on unsigned numbers can overflow the capacity of hardware to represent the result, so can an operation on two's complement numbers. Overflow occurs when the leftmost retained bit of the binary bit pattern is not the same as the infinite number of digits to the left (the sign bit is incorrect): a 0 on the left of the bit pattern when the number is negative or a 1 when the number is positive.

Unlike the numbers discussed above, memory addresses naturally start at 0 and continue to the largest address. Put another way, negative addresses make no sense. Thus, programs want to deal sometimes with numbers that can be positive or negative and sometimes with numbers that can be only positive. Some programming languages reflect this distinction. C, for example, names the former *integers* (declared as `int` in the program) and the latter *unsigned integers* (`unsigned int`). Some C style guides even recommend declaring the former as `signed int` to keep the distinction clear.

Hardware/ Software Interface

Let's examine two useful shortcuts when working with two's complement numbers. The first shortcut is a quick way to negate a two's complement binary number. Simply invert every 0 to 1 and every 1 to 0, then add one to the result. This shortcut is based on the observation that the sum of a number and its inverted representation must be $111 \dots 111_{\text{two}}$, which represents -1 . Since $x + \bar{x} = -1$, therefore $x + \bar{x} + 1 = 0$ or $\bar{x} + 1 = -x$.

Negation Shortcut

Negate 2_{ten} , and then check the result by negating -2_{ten} .

EXAMPLE

$$2_{\text{ten}} = 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0010_{\text{two}}$$

ANSWER

Negating this number by inverting the bits and adding one,

$$\begin{array}{r} 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1101_{\text{two}} \\ + \hspace{10em} 1_{\text{two}} \\ \hline = & 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1110_{\text{two}} \\ = & -2_{\text{ten}} \end{array}$$

Let's negate the 16-bit version of 2 using the earlier shortcut. Thus,

$0000\ 0000\ 0000\ 0010_{\text{two}}$

becomes

$$\begin{array}{r} 1111\ 1111\ 1111\ 1101_{\text{two}} \\ + \qquad \qquad \qquad 1_{\text{two}} \\ \hline = 1111\ 1111\ 1111\ 1110_{\text{two}} \end{array}$$

Creating a 32-bit version of the negative number means copying the sign bit 16 times and placing it on the left:

$1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1110_{\text{two}} = -2_{\text{ten}}$

This trick works because positive two's complement numbers really have an infinite number of 0s on the left and negative two's complement numbers have an infinite number of 1s. The binary bit pattern representing a number hides leading bits to fit the width of the hardware; sign extension simply restores some of them.

Summary

The main point of this section is that we need to represent both positive and negative integers within a computer word, and although there are pros and cons to any option, the overwhelming choice since 1965 has been two's complement.

What is the decimal value of this 64-bit two's complement number?

$1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1000_{\text{two}}$

Check Yourself

- 1) -4_{ten}
- 2) -8_{ten}
- 3) -16_{ten}
- 4) $18,446,744,073,709,551,609_{\text{ten}}$

Elaboration: Two's complement gets its name from the rule that the unsigned sum of an n -bit number and its negative is 2^n ; hence, the complement or negation of a two's complement number x is $2^n - x$.

one's complement

A notation that represents the most negative value by $10 \dots 00_{\text{two}}$ and the most positive value by $01 \dots 11_{\text{two}}$, leaving an equal number of negatives and positives but ending up with two zeros, one positive ($00 \dots 00_{\text{two}}$) and one negative ($11 \dots 11_{\text{two}}$). The term is also used to mean the inversion of every bit in a pattern: 0 to 1 and 1 to 0.

biased notation

A notation that represents the most negative value by $00 \dots 00_{\text{two}}$ and the most positive value by $11 \dots 11_{\text{two}}$, with 0 typically having the value $10 \dots 00_{\text{two}}$, thereby biasing the number such that the number plus the bias has a nonnegative representation.

A third alternative representation to two's complement and sign and magnitude is called **one's complement**. The negative of a one's complement is found by inverting each bit, from 0 to 1 and from 1 to 0, which helps explain its name since the complement of x is $2^n - x - 1$. It was also an attempt to be a better solution than sign and magnitude, and several early scientific computers did use the notation. This representation is similar to two's complement except that it also has two 0s: $00 \dots 00_{\text{two}}$ is positive 0 and $11 \dots 11_{\text{two}}$ is negative 0. The most negative number, $10 \dots 00_{\text{two}}$, represents $-2,147,483,647_{\text{ten}}$, and so the positives and negatives are balanced. One's complement adders did need an extra step to subtract a number, and hence two's complement dominates today.

A final notation, which we will look at when we discuss floating point in Chapter 3, is to represent the most negative value by $00 \dots 00_{\text{two}}$ and the most positive value by $11 \dots 11_{\text{two}}$, with 0 typically having the value $10 \dots 00_{\text{two}}$. This is called a **biased notation**, since it biases the number such that the number plus the bias has a non-negative representation.

Elaboration: For signed decimal numbers, we used “–” to represent negative because there are no limits to the size of a decimal number. Given a fixed word size, binary and hexadecimal (see Figure 2.4) bit strings can encode the sign; hence we do not normally use “+” or “–” with binary or hexadecimal notation.

2.5**Representing Instructions in the Computer**

We are now ready to explain the difference between the way humans instruct computers and the way computers see instructions.

Instructions are kept in the computer as a series of high and low electronic signals and may be represented as numbers. In fact, each piece of an instruction can be considered as an individual number, and placing these numbers side by side forms the instruction.

Since registers are referred to by almost all instructions, there must be a convention to map register names into numbers. In MIPS assembly language, registers \$s0 to \$s7 map onto registers 16 to 23, and registers \$t0 to \$t7 map onto registers 8 to 15. Hence, \$s0 means register 16, \$s1 means register 17, \$s2 means register 18, ..., \$t0 means register 8, \$t1 means register 9, and so on. We'll describe the convention for the rest of the 32 registers in the following sections.

Translating a MIPS Assembly Instruction into a Machine Instruction

Let's do the next step in the refinement of the MIPS language as an example. We'll show the real MIPS language version of the instruction represented symbolically as

`add $t0,$s1,$s2`

first as a combination of decimal numbers and then of binary numbers.

EXAMPLE

The decimal representation is

0	17	18	8	0	32
---	----	----	---	---	----

ANSWER

Each of these segments of an instruction is called a *field*. The first and last fields (containing 0 and 32 in this case) in combination tell the MIPS computer that this instruction performs addition. The second field gives the number of the register that is the first source operand of the addition operation ($17 = \$s1$), and the third field gives the other source operand for the addition ($18 = \$s2$). The fourth field contains the number of the register that is to receive the sum ($8 = \$t0$). The fifth field is unused in this instruction, so it is set to 0. Thus, this instruction adds register $\$s1$ to register $\$s2$ and places the sum in register $\$t0$.

This instruction can also be represented as fields of binary numbers as opposed to decimal:

000000	10001	10010	01000	00000	100000
6 bits	5 bits	5 bits	5 bits	5 bits	6 bits

This layout of the instruction is called the **instruction format**. As you can see from counting the number of bits, this MIPS instruction takes exactly 32 bits—the same size as a data word. In keeping with our design principle that simplicity favors regularity, all MIPS instructions are 32 bits long.

To distinguish it from assembly language, we call the numeric version of instructions **machine language** and a sequence of such instructions **machine code**.

It would appear that you would now be reading and writing long, tedious strings of binary numbers. We avoid that tedium by using a higher base than binary that converts easily into binary. Since almost all computer data sizes are multiples of 4, **hexadecimal** (base 16) numbers are popular. Since base 16 is a power of 2, we can trivially convert by replacing each group of four binary digits by a single hexadecimal digit, and vice versa. Figure 2.4 converts between hexadecimal and binary.

instruction format
A form of representation of an instruction composed of fields of binary numbers.

machine language
Binary representation used for communication within a computer system.

hexadecimal
Numbers in base 16.

Hexadecimal	Binary	Hexadecimal	Binary	Hexadecimal	Binary	Hexadecimal	Binary
0 _{hex}	0000 _{two}	4 _{hex}	0100 _{two}	8 _{hex}	1000 _{two}	c _{hex}	1100 _{two}
1 _{hex}	0001 _{two}	5 _{hex}	0101 _{two}	9 _{hex}	1001 _{two}	d _{hex}	1101 _{two}
2 _{hex}	0010 _{two}	6 _{hex}	0110 _{two}	a _{hex}	1010 _{two}	e _{hex}	1110 _{two}
3 _{hex}	0011 _{two}	7 _{hex}	0111 _{two}	b _{hex}	1011 _{two}	f _{hex}	1111 _{two}

FIGURE 2.4 The hexadecimal-binary conversion table. Just replace one hexadecimal digit by the corresponding four binary digits, and vice versa. If the length of the binary number is not a multiple of 4, go from right to left.

Because we frequently deal with different number bases, to avoid confusion we will subscript decimal numbers with *ten*, binary numbers with *two*, and hexadecimal numbers with *hex*. (If there is no subscript, the default is base 10.) By the way, C and Java use the notation `0xnnnn` for hexadecimal numbers.

EXAMPLE

ANSWER

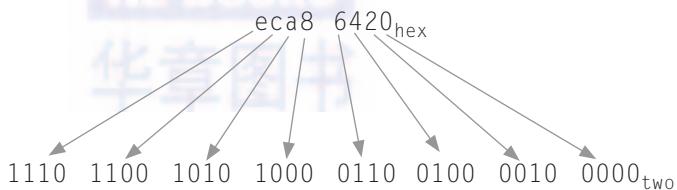
Binary to Hexadecimal and Back

Convert the following hexadecimal and binary numbers into the other base:

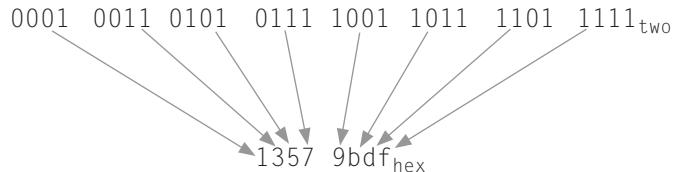
eca8 6420_{hex}

0001 0011 0101 0111 1001 1011 1101 1111_{two}

Using Figure 2.4, the answer is just a table lookup one way:



And then the other direction:



MIPS Fields

MIPS fields are given names to make them easier to discuss:

op	rs	rt	rd	shamt	funct
6 bits	5 bits	5 bits	5 bits	5 bits	6 bits

Here is the meaning of each name of the fields in MIPS instructions:

- *op*: Basic operation of the instruction, traditionally called the **opcode**.
- *rs*: The first register source operand.
- *rt*: The second register source operand.
- *rd*: The register destination operand. It gets the result of the operation.
- *shamt*: Shift amount. (Section 2.6 explains shift instructions and this term; it will not be used until then, and hence the field contains zero in this section.)
- *funct*: Function. This field, often called the *function code*, selects the specific variant of the operation in the op field.

opcode The field that denotes the operation and format of an instruction.

A problem occurs when an instruction needs longer fields than those shown above. For example, the load word instruction must specify two registers and a constant. If the address were to use one of the 5-bit fields in the format above, the constant within the load word instruction would be limited to only 2^5 or 32. This constant is used to select elements from arrays or data structures, and it often needs to be much larger than 32. This 5-bit field is too small to be useful.

Hence, we have a conflict between the desire to keep all instructions the same length and the desire to have a single instruction format. This leads us to the final hardware design principle:

Design Principle 4: Good design demands good compromises.

The compromise chosen by the MIPS designers is to keep all instructions the same length, thereby requiring different kinds of instruction formats for different kinds of instructions. For example, the format above is called *R-type* (for register) or *R-format*. A second type of instruction format is called *I-type* (for immediate) or *I-format* and is used by the immediate and data transfer instructions. The fields of I-format are

op	rs	rt	constant or address
6 bits	5 bits	5 bits	16 bits

The 16-bit address means a load word instruction can load any word within a region of $\pm 2^{15}$ or 32,768 bytes ($\pm 2^{13}$ or 8192 words) of the address in the base register rs. Similarly, add immediate is limited to constants no larger than $\pm 2^{15}$. We see that more than 32 registers would be difficult in this format, as the rs and rt fields would each need another bit, making it harder to fit everything in one word.

Let's look at the load word instruction from page 83:

```
lw    $t0,32($s3)    # Temporary reg $t0 gets A[8]
```

Here, 19 (for \$s3) is placed in the rs field, 8 (for \$t0) is placed in the rt field, and 32 is placed in the address field. Note that the meaning of the rt field has changed for this instruction: in a load word instruction, the rt field specifies the *destination* register, which receives the result of the load.

Although multiple formats complicate the hardware, we can reduce the complexity by keeping the formats similar. For example, the first three fields of the R-type and I-type formats are the same size and have the same names; the length of the fourth field in I-type is equal to the sum of the lengths of the last three fields of R-type.

In case you were wondering, the formats are distinguished by the values in the first field: each format is assigned a distinct set of values in the first field (op) so that the hardware knows whether to treat the last half of the instruction as three fields (R-type) or as a single field (I-type). Figure 2.5 shows the numbers used in each field for the MIPS instructions covered here.

Instruction	Format	op	rs	rt	rd	shamt	funct	address
add	R	0	reg	reg	reg	0	32_{ten}	n.a.
sub (subtract)	R	0	reg	reg	reg	0	34_{ten}	n.a.
add immediate	I	8_{ten}	reg	reg	n.a.	n.a.	n.a.	constant
lw (load word)	I	35_{ten}	reg	reg	n.a.	n.a.	n.a.	address
sw (store word)	I	43_{ten}	reg	reg	n.a.	n.a.	n.a.	address

FIGURE 2.5 MIPS instruction encoding. In the table above, “reg” means a register number between 0 and 31, “address” means a 16-bit address, and “n.a.” (not applicable) means this field does not appear in this format. Note that add and sub instructions have the same value in the op field; the hardware uses the funct field to decide the variant of the operation: add (32) or subtract (34).

EXAMPLE

Translating MIPS Assembly Language into Machine Language

We can now take an example all the way from what the programmer writes to what the computer executes. If \$t1 has the base of the array A and \$s2 corresponds to h, the assignment statement

$A[300] = h + A[300];$

is compiled into

```
lw    $t0,1200($t1)# Temporary reg $t0 gets A[300]
add  $t0,$s2,$t0  # Temporary reg $t0 gets h + A[300]
sw    $t0,1200($t1) # Stores h + A[300] back into A[300]
```

What is the MIPS machine language code for these three instructions?

For convenience, let's first represent the machine language instructions using decimal numbers. From Figure 2.5, we can determine the three machine language instructions:

ANSWER

op	rs	rt	rd	address/ shamt	funct
35	9	8	1200		
0	18	8	8	0	32
43	9	8	1200		

The `lw` instruction is identified by 35 (see Figure 2.5) in the first field (op). The base register 9 (`$t1`) is specified in the second field (rs), and the destination register 8 (`$t0`) is specified in the third field (rt). The offset to select A[300] ($1200 = 300 \times 4$) is found in the final field (address).

The `add` instruction that follows is specified with 0 in the first field (op) and 32 in the last field (funct). The three register operands (18, 8, and 8) are found in the second, third, and fourth fields and correspond to `$s2`, `$t0`, and `$t0`.

The `sw` instruction is identified with 43 in the first field. The rest of this final instruction is identical to the `lw` instruction.

Since $1200_{\text{ten}} = 0000\ 0100\ 1011\ 0000_{\text{two}}$, the binary equivalent to the decimal form is:

100011	01001	01000	0000 0100 1011 0000		
000000	10010	01000	01000	00000	100000
101011	01001	01000	0000 0100 1011 0000		

Note the similarity of the binary representations of the first and last instructions. The only difference is in the third bit from the left, which is highlighted here.

Figure 2.6 summarizes the portions of MIPS machine language described in this section. As we shall see in Chapter 4, the similarity of the binary representations of related instructions simplifies hardware design. These similarities are another example of regularity in the MIPS architecture.

MIPS machine language

Name	Format	Example						Comments
add	R	0	18	19	17	0	32	add \$s1,\$s2,\$s3
sub	R	0	18	19	17	0	34	sub \$s1,\$s2,\$s3
addi	I	8	18	17	100			addi \$s1,\$s2,100
lw	I	35	18	17	100			lw \$s1,100(\$s2)
sw	I	43	18	17	100			sw \$s1,100(\$s2)
Field size		6 bits	5 bits	5 bits	5 bits	5 bits	6 bits	All MIPS instructions are 32 bits long
R-format	R	op	rs	rt	rd	shamt	funct	Arithmetic instruction format
I-format	I	op	rs	rt	address			Data transfer format

FIGURE 2.6 MIPS architecture revealed through Section 2.5. The two MIPS instruction formats so far are R and I. The first 16 bits are the same: both contain an *op* field, giving the base operation; an *rs* field, giving one of the sources; and the *rt* field, which specifies the other source operand, except for load word, where it specifies the destination register. R-format divides the last 16 bits into an *rd* field, specifying the destination register; the *shamt* field, which Section 2.6 explains; and the *funct* field, which specifies the specific operation of R-format instructions. I-format combines the last 16 bits into a single *address* field.

The BIG Picture

Today's computers are built on two key principles:

1. Instructions are represented as numbers.
2. Programs are stored in memory to be read or written, just like numbers.

These principles lead to the *stored-program* concept; its invention let the computing genie out of its bottle. Figure 2.7 shows the power of the concept; specifically, memory can contain the source code for an editor program, the corresponding compiled machine code, the text that the compiled program is using, and even the compiler that generated the machine code.

One consequence of instructions as numbers is that programs are often shipped as files of binary numbers. The commercial implication is that computers can inherit ready-made software provided they are compatible with an existing instruction set. Such “binary compatibility” often leads industry to align around a small number of instruction set architectures.

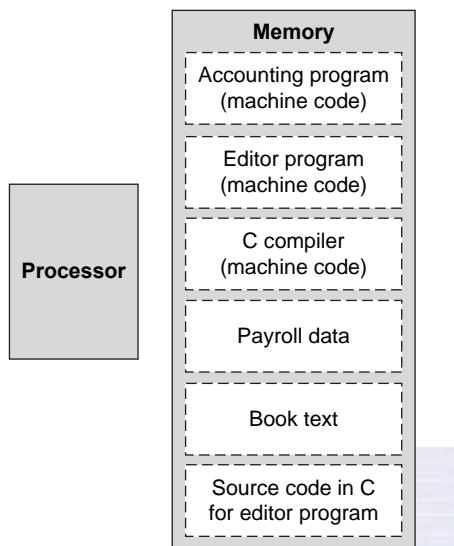


FIGURE 2.7 The stored-program concept. Stored programs allow a computer that performs accounting to become, in the blink of an eye, a computer that helps an author write a book. The switch happens simply by loading memory with programs and data and then telling the computer to begin executing at a given location in memory. Treating instructions in the same way as data greatly simplifies both the memory hardware and the software of computer systems. Specifically, the memory technology needed for data can also be used for programs, and programs like compilers, for instance, can translate code written in a notation far more convenient for humans into code that the computer can understand.

What MIPS instruction does this represent? Choose from one of the four options below.

Check Yourself

op	rs	rt	rd	shamt	funct
0	8	9	10	0	34

1. add \$s0, \$s1, \$s2
2. add \$s2, \$s0, \$s1
3. add \$s2, \$s1, \$s0
4. sub \$s2, \$s0, \$s1

*“Contrariwise,”
continued Tweedledee,
“if it was so, it might
be; and if it were so,
it would be; but as it
isn’t, it ain’t. That’s
logic.”*

Lewis Carroll, *Alice’s Adventures in Wonderland*, 1865

2.6

Logical Operations

Although the first computers operated on full words, it soon became clear that it was useful to operate on fields of bits within a word or even on individual bits. Examining characters within a word, each of which is stored as 8 bits, is one example of such an operation (see Section 2.9). It follows that operations were added to programming languages and instruction set architectures to simplify, among other things, the packing and unpacking of bits into words. These instructions are called logical operations. Figure 2.8 shows logical operations in C, Java, and MIPS.

Logical operations	C operators	Java operators	MIPS instructions
Shift left	<<	<<	sll
Shift right	>>	>>>	srl
Bit-by-bit AND	&	&	and, andi
Bit-by-bit OR			or, ori
Bit-by-bit NOT	~	~	nor

FIGURE 2.8 C and Java logical operators and their corresponding MIPS instructions. MIPS implements NOT using a NOR with one operand being zero.

The first class of such operations is called *shifts*. They move all the bits in a word to the left or right, filling the emptied bits with 0s. For example, if register \$s0 contained

$$0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 1001_{\text{two}} = 9_{\text{ten}}$$

and the instruction to shift left by 4 was executed, the new value would be:

$$0000\ 0000\ 0000\ 0000\ 0000\ 0001\ 0000_{\text{two}} = 144_{\text{ten}}$$

The dual of a shift left is a shift right. The actual name of the two MIPS shift instructions are called *shift left logical* (sll) and *shift right logical* (srl). The following

instruction performs the operation above, assuming that the original value was in register \$s0 and the result should go in register \$t2:

```
sll    $t2,$s0,4    # reg $t2 = reg $s0 << 4 bits
```

We delayed explaining the *shamt* field in the R-format. Used in shift instructions, it stands for *shift amount*. Hence, the machine language version of the instruction above is

op	rs	rt	rd	shamt	funct
0	0	16	10	4	0

The encoding of sll is 0 in both the op and funct fields, rd contains 10 (register \$t2), rt contains 16 (register \$s0), and shamt contains 4. The rs field is unused and thus is set to 0.

Shift left logical provides a bonus benefit. Shifting left by i bits gives the same result as multiplying by 2^i , just as shifting a decimal number by i digits is equivalent to multiplying by 10^i . For example, the above sll shifts by 4, which gives the same result as multiplying by 2^4 or 16. The first bit pattern above represents 9, and $9 \times 16 = 144$, the value of the second bit pattern.

Another useful operation that isolates fields is **AND**. (We capitalize the word to avoid confusion between the operation and the English conjunction.) AND is a bit-by-bit operation that leaves a 1 in the result only if both bits of the operands are 1. For example, if register \$t2 contains

0000 0000 0000 0000 0000 1101 1100 0000_{two}

and register \$t1 contains

0000 0000 0000 0000 0011 1100 0000 0000_{two}

then, after executing the MIPS instruction

```
and $t0,$t1,$t2    # reg $t0 = reg $t1 & reg $t2
```

the value of register \$t0 would be

0000 0000 0000 0000 0000 1100 0000 0000_{two}

AND A logical bit-by-bit operation with two operands that calculates a 1 only if there is a 1 in *both* operands.

OR A logical bit-by-bit operation with two operands that calculates a 1 if there is a 1 in *either* operand.

As you can see, AND can apply a bit pattern to a set of bits to force 0s where there is a 0 in the bit pattern. Such a bit pattern in conjunction with AND is traditionally called a *mask*, since the mask “conceals” some bits.

To place a value into one of these seas of 0s, there is the dual to AND, called **OR**. It is a bit-by-bit operation that places a 1 in the result if *either* operand bit is a 1. To elaborate, if the registers \$t1 and \$t2 are unchanged from the preceding example, the result of the MIPS instruction

```
or $t0,$t1,$t2 # reg $t0 = reg $t1 | reg $t2
```

is this value in register \$t0:

0000 0000 0000 0000 0011 1101 1100 0000_{two}

NOT A logical bit-by-bit operation with one operand that inverts the bits; that is, it replaces every 1 with a 0, and every 0 with a 1.

The final logical operation is a contrarian. **NOT** takes one operand and places a 1 in the result if one operand bit is a 0, and vice versa. In keeping with the three-operand format, the designers of MIPS decided to include the instruction **NOR** (NOT OR) instead of NOT. If one operand is zero, then it is equivalent to NOT: A NOR 0 = NOT (A OR 0) = NOT (A).

If the register \$t1 is unchanged from the preceding example and register \$t3 has the value 0, the result of the MIPS instruction

```
nor $t0,$t1,$t3 # reg $t0 = ~ (reg $t1 | reg $t3)
```

is this value in register \$t0:

1111 1111 1111 1111 1100 0011 1111 1111_{two}

Figure 2.8 above shows the relationship between the C and Java operators and the MIPS instructions. Constants are useful in AND and OR logical operations as well as in arithmetic operations, so MIPS also provides the instructions *and immediate* (andi) and *or immediate* (ori). Constants are rare for NOR, since its main use is to invert the bits of a single operand; thus, the MIPS instruction set architecture has no immediate version.

Elaboration: The full MIPS instruction set also includes exclusive or (XOR), which sets the bit to 1 when two corresponding bits differ, and to 0 when they are the same. C allows *bit fields* or *fields* to be defined within words, both allowing objects to be

packed within a word and to match an externally enforced interface such as an I/O device. All fields must fit within a single word. Fields are unsigned integers that can be as short as 1 bit. C compilers insert and extract fields using logical instructions in MIPS: and, or, sll, and srl.

Which operations can isolate a field in a word?

1. AND
2. A shift left followed by a shift right

Check Yourself

The utility of an automatic computer lies in the possibility of using a given sequence of instructions repeatedly, the number of times it is iterated being dependent upon the results of the computation. ... This choice can be made to depend upon the sign of a number (zero being reckoned as plus for machine purposes). Consequently, we introduce an [instruction] (the conditional transfer [instruction]) which will, depending on the sign of a given number, cause the proper one of two routines to be executed.

Burks, Goldstine, and von Neumann, 1947

2.7

Instructions for Making Decisions

What distinguishes a computer from a simple calculator is its ability to make decisions. Based on the input data and the values created during computation, different instructions execute. Decision making is commonly represented in programming languages using the *if* statement, sometimes combined with *go to* statements and labels. MIPS assembly language includes two decision-making instructions, similar to an *if* statement with a *go to*. The first instruction is

```
beq register1, register2, L1
```

This instruction means go to the statement labeled L1 if the value in register1 equals the value in register2. The mnemonic *beq* stands for *branch if equal*. The second instruction is

```
bne register1, register2, L1
```

It means go to the statement labeled L1 if the value in register1 does *not* equal the value in register2. The mnemonic *bne* stands for *branch if not equal*. These two instructions are traditionally called **conditional branches**.

conditional branch
An instruction that requires the comparison of two values and that allows for a subsequent transfer of control to a new address in the program based on the outcome of the comparison.

EXAMPLE**ANSWER****Compiling *if-then-else* into Conditional Branches**

In the following code segment, f, g, h, i, and j are variables. If the five variables f through j correspond to the five registers \$s0 through \$s4, what is the compiled MIPS code for this C *if* statement?

```
if (i == j) f = g + h; else f = g - h;
```

Figure 2.9 is a flowchart of what the MIPS code should do. The first expression compares for equality, so it would seem that we would want the branch if registers are equal instruction (beq). In general, the code will be more efficient if we test for the opposite condition to branch over the code that performs the subsequent *then* part of the *if* (the label *Else* is defined below) and so we use the branch if registers are *not* equal instruction (bne):

```
bne $s3,$s4,Else    # go to Else if i ≠ j
```

The next assignment statement performs a single operation, and if all the operands are allocated to registers, it is just one instruction:

```
add $s0,$s1,$s2    # f = g + h (skipped if i ≠ j)
```

We now need to go to the end of the *if* statement. This example introduces another kind of branch, often called an *unconditional branch*. This instruction says that the processor always follows the branch. To distinguish between conditional and unconditional branches, the MIPS name for this type of instruction is *jump*, abbreviated as j (the label *Exit* is defined below).

```
j Exit      # go to Exit
```

The assignment statement in the *else* portion of the *if* statement can again be compiled into a single instruction. We just need to append the label *Else* to this instruction. We also show the label *Exit* that is after this instruction, showing the end of the *if-then-else* compiled code:

```
Else:sub $s0,$s1,$s2    # f = g - h (skipped if i = j)
Exit:
```

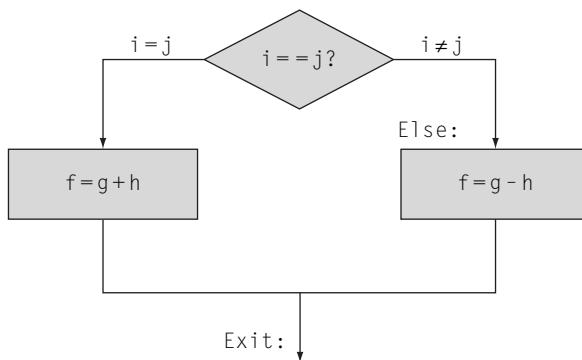


FIGURE 2.9 Illustration of the options in the *if* statement above. The left box corresponds to the *then* part of the *if* statement, and the right box corresponds to the *else* part.

Notice that the assembler relieves the compiler and the assembly language programmer from the tedium of calculating addresses for branches, just as it does for calculating data addresses for loads and stores (see Section 2.12).

Compilers frequently create branches and labels where they do not appear in the programming language. Avoiding the burden of writing explicit labels and branches is one benefit of writing in high-level programming languages and is a reason coding is faster at that level.

Hardware/ Software Interface

Loops

Decisions are important both for choosing between two alternatives—found in *if* statements—and for iterating a computation—found in loops. The same assembly instructions are the building blocks for both cases.

Compiling a *while* Loop in C

Here is a traditional loop in C:

```
while (save[i] == k)
    i += 1;
```

Assume that *i* and *k* correspond to registers \$s3 and \$s5 and the base of the array *save* is in \$s6. What is the MIPS assembly code corresponding to this C segment?

EXAMPLE

ANSWER

The first step is to load `save[i]` into a temporary register. Before we can load `save[i]` into a temporary register, we need to have its address. Before we can add `i` to the base of array `save` to form the address, we must multiply the index `i` by 4 due to the byte addressing problem. Fortunately, we can use shift left logical, since shifting left by 2 bits multiplies by 2^2 or 4 (see page 103 in the prior section). We need to add the label `Loop` to it so that we can branch back to that instruction at the end of the loop:

```
Loop: sll    $t1,$s3,2      # Temp reg $t1 = i * 4
```

To get the address of `save[i]`, we need to add `$t1` and the base of `save` in `$s6`:

```
add $t1,$t1,$s6      # $t1 = address of save[i]
```

Now we can use that address to load `save[i]` into a temporary register:

```
lw    $t0,0($t1)      # Temp reg $t0 = save[i]
```

The next instruction performs the loop test, exiting if `save[i] ≠ k`:

```
bne   $t0,$s5, Exit  # go to Exit if save[i] ≠ k
```

The next instruction adds 1 to `i`:

```
addi  $s3,$s3,1      # i = i + 1
```

The end of the loop branches back to the *while* test at the top of the loop. We just add the `Exit` label after it, and we're done:

```
j     Loop          # go to Loop
```

Exit:

(See the exercises for an optimization of this sequence.)

Hardware/ Software Interface

Such sequences of instructions that end in a branch are so fundamental to compiling that they are given their own buzzword: a **basic block** is a sequence of instructions without branches, except possibly at the end, and without branch targets or branch labels, except possibly at the beginning. One of the first early phases of compilation is breaking the program into basic blocks.

basic block A sequence of instructions without branches (except possibly at the end) and without branch targets or branch labels (except possibly at the beginning).

The test for equality or inequality is probably the most popular test, but sometimes it is useful to see if a variable is less than another variable. For example, a *for* loop may want to test to see if the index variable is less than 0. Such comparisons are accomplished in MIPS assembly language with an instruction that compares two

registers and sets a third register to 1 if the first is less than the second; otherwise, it is set to 0. The MIPS instruction is called *set on less than*, or `slt`. For example,

```
slt      $t0, $s3, $s4    # $t0 = 1 if $s3 < $s4
```

means that register `$t0` is set to 1 if the value in register `$s3` is less than the value in register `$s4`; otherwise, register `$t0` is set to 0.

Constant operands are popular in comparisons, so there is an immediate version of the set on less than instruction. To test if register `$s2` is less than the constant 10, we can just write

```
slti     $t0,$s2,10      # $t0 = 1 if $s2 < 10
```

Hardware/ Software Interface

MIPS compilers use the `slt`, `slti`, `beq`, `bne`, and the fixed value of 0 (always available by reading register `$zero`) to create all relative conditions: equal, not equal, less than, less than or equal, greater than, greater than or equal.

Heeding von Neumann's warning about the simplicity of the "equipment," the MIPS architecture doesn't include branch on less than because it is too complicated; either it would stretch the clock cycle time or it would take extra clock cycles per instruction. Two faster instructions are more useful.

Hardware/ Software Interface

Comparison instructions must deal with the dichotomy between signed and unsigned numbers. Sometimes a bit pattern with a 1 in the most significant bit represents a negative number and, of course, is less than any positive number, which must have a 0 in the most significant bit. With unsigned integers, on the other hand, a 1 in the most significant bit represents a number that is *larger* than any that begins with a 0. (We'll soon take advantage of this dual meaning of the most significant bit to reduce the cost of the array bounds checking.)

MIPS offers two versions of the set on less than comparison to handle these alternatives. *Set on less than* (`slt`) and *set on less than immediate* (`slti`) work with signed integers. Unsigned integers are compared using *set on less than unsigned* (`sltu`) and *set on less than immediate unsigned* (`sltiu`).

EXAMPLE**Signed versus Unsigned Comparison**

Suppose register \$s0 has the binary number

1111 1111 1111 1111 1111 1111 1111 1111_{two}

and that register \$s1 has the binary number

0000 0000 0000 0000 0000 0000 0000 0001_{two}

What are the values of registers \$t0 and \$t1 after these two instructions?

```
slt      $t0, $s0, $s1 # signed comparison
sltu     $t1, $s0, $s1 # unsigned comparison
```

ANSWER

The value in register \$s0 represents -1_{ten} if it is an integer and $4,294,967,295_{ten}$ if it is an unsigned integer. The value in register \$s1 represents 1_{ten} in either case. Then register \$t0 has the value 1, since $-1_{ten} < 1_{ten}$, and register \$t1 has the value 0, since $4,294,967,295_{ten} > 1_{ten}$.

Treating signed numbers as if they were unsigned gives us a low cost way of checking if $0 \leq x < y$, which matches the index out-of-bounds check for arrays. The key is that negative integers in two's complement notation look like large numbers in unsigned notation; that is, the most significant bit is a sign bit in the former notation but a large part of the number in the latter. Thus, an unsigned comparison of $x < y$ also checks if x is negative as well as if x is less than y .

EXAMPLE**Bounds Check Shortcut**

Use this shortcut to reduce an index-out-of-bounds check: jump to IndexOutOfBounds if $\$s1 \geq \$t2$ or if $\$s1$ is negative.

ANSWER

The checking code just uses sltu to do both checks:

```
sltu $t0,$s1,$t2 # $t0=0 if $s1>=length or $s1<0
beq  $t0,$zero,IndexOutOfBounds #if bad, goto Error
```

Case/Switch Statement

Most programming languages have a *case* or *switch* statement that allows the programmer to select one of many alternatives depending on a single value. The simplest way to implement *switch* is via a sequence of conditional tests, turning the *switch* statement into a chain of *if-then-else* statements.

Sometimes the alternatives may be more efficiently encoded as a table of addresses of alternative instruction sequences, called a **jump address table** or **jump table**, and the program needs only to index into the table and then jump to the appropriate sequence. The jump table is then just an array of words containing addresses that correspond to labels in the code. The program loads the appropriate entry from the jump table into a register. It then needs to jump using the address in the register. To support such situations, computers like MIPS include a *jump register* instruction (*jr*), meaning an unconditional jump to the address specified in a register. Then it jumps to the proper address using this instruction, which is described in the next section.

jump address table
Also called **jump table**.
A table of addresses of alternative instruction sequences.

Although there are many statements for decisions and loops in programming languages like C and Java, the bedrock statement that implements them at the instruction set level is the conditional branch.

Hardware/ Software Interface

Elaboration: If you have heard about *delayed branches*, covered in Chapter 4, don't worry: the MIPS assembler makes them invisible to the assembly language programmer.

I. C has many statements for decisions and loops, while MIPS has few. Which of the following do or do not explain this imbalance? Why?

1. More decision statements make code easier to read and understand.
2. Fewer decision statements simplify the task of the underlying layer that is responsible for execution.
3. More decision statements mean fewer lines of code, which generally reduces coding time.
4. More decision statements mean fewer lines of code, which generally results in the execution of fewer operations.

Check Yourself

II. Why does C provide two sets of operators for AND (& and &&) and two sets of operators for OR (| and ||), while MIPS doesn't?

1. Logical operations AND and OR implement & and |, while conditional branches implement && and ||.
2. The previous statement has it backwards: && and || correspond to logical operations, while & and | map to conditional branches.
3. They are redundant and mean the same thing: && and || are simply inherited from the programming language B, the predecessor of C.

2.8

Supporting Procedures in Computer Hardware

procedure A stored subroutine that performs a specific task based on the parameters with which it is provided.

A **procedure** or function is one tool programmers use to structure programs, both to make them easier to understand and to allow code to be reused. Procedures allow the programmer to concentrate on just one portion of the task at a time; parameters act as an interface between the procedure and the rest of the program and data, since they can pass values and return results. We describe the equivalent to procedures in Java in Section 2.15 on the CD, but Java needs everything from a computer that C needs.

You can think of a procedure like a spy who leaves with a secret plan, acquires resources, performs the task, covers his or her tracks, and then returns to the point of origin with the desired result. Nothing else should be perturbed once the mission is complete. Moreover, a spy operates on only a “need to know” basis, so the spy can't make assumptions about his employer.

Similarly, in the execution of a procedure, the program must follow these six steps:

1. Put parameters in a place where the procedure can access them.
2. Transfer control to the procedure.
3. Acquire the storage resources needed for the procedure.
4. Perform the desired task.
5. Put the result value in a place where the calling program can access it.
6. Return control to the point of origin, since a procedure can be called from several points in a program.

As mentioned above, registers are the fastest place to hold data in a computer, so we want to use them as much as possible. MIPS software follows the following convention for procedure calling in allocating its 32 registers:

- \$a0–\$a3: four argument registers in which to pass parameters
- \$v0–\$v1: two value registers in which to return values
- \$ra: one return address register to return to the point of origin

In addition to allocating these registers, MIPS assembly language includes an instruction just for the procedures: it jumps to an address and simultaneously saves the address of the following instruction in register \$ra. The **jump-and-link instruction** (`jal`) is simply written

```
jal ProcedureAddress
```

The *link* portion of the name means that an address or link is formed that points to the calling site to allow the procedure to return to the proper address. This “link,” stored in register \$ra (register 31), is called the **return address**. The return address is needed because the same procedure could be called from several parts of the program.

To support such situations, computers like MIPS use *jump register* instruction (`jr`), introduced above to help with case statements, meaning an unconditional jump to the address specified in a register:

```
jr $ra
```

Jump register instruction jumps to the address stored in register \$ra—which is just what we want. Thus, the calling program, or **caller**, puts the parameter values in \$a0–\$a3 and uses `jal X` to jump to procedure X (sometimes named the **callee**). The callee then performs the calculations, places the results in \$v0 and \$v1, and returns control to the caller using `jr $ra`.

Implicit in the stored-program idea is the need to have a register to hold the address of the current instruction being executed. For historical reasons, this register is almost always called the **program counter**, abbreviated *PC* in the MIPS architecture, although a more sensible name would have been *instruction address register*. The `jal` instruction actually saves $PC + 4$ in register \$ra to link to the following instruction to set up the procedure return.

jump-and-link instruction An instruction that jumps to an address and simultaneously saves the address of the following instruction in a register (\$ra in MIPS).

return address A link to the calling site that allows a procedure to return to the proper address; in MIPS it is stored in register \$ra.

caller The program that instigates a procedure and provides the necessary parameter values.

callee A procedure that executes a series of stored instructions based on parameters provided by the caller and then returns control to the caller.

program counter (PC) The register containing the address of the instruction in the program being executed.

Using More Registers

stack A data structure for spilling registers organized as a last-in-first-out queue.

stack pointer A value denoting the most recently allocated address in a stack that shows where registers should be spilled or where old register values can be found. In MIPS, it is register \$sp.

push Add element to stack.

pop Remove element from stack.

Suppose a compiler needs more registers for a procedure than the four argument and two return value registers. Since we must cover our tracks after our mission is complete, any registers needed by the caller must be restored to the values that they contained *before* the procedure was invoked. This situation is an example in which we need to spill registers to memory, as mentioned in the *Hardware/Software Interface* section.

The ideal data structure for spilling registers is a **stack**—a last-in-first-out queue. A stack needs a pointer to the most recently allocated address in the stack to show where the next procedure should place the registers to be spilled or where old register values are found. The **stack pointer** is adjusted by one word for each register that is saved or restored. MIPS software reserves register 29 for the stack pointer, giving it the obvious name \$sp. Stacks are so popular that they have their own buzzwords for transferring data to and from the stack: placing data onto the stack is called a **push**, and removing data from the stack is called a **pop**.

By historical precedent, stacks “grow” from higher addresses to lower addresses. This convention means that you push values onto the stack by subtracting from the stack pointer. Adding to the stack pointer shrinks the stack, thereby popping values off the stack.

EXAMPLE

Compiling a C Procedure That Doesn’t Call Another Procedure

Let’s turn the example on page 79 from Section 2.2 into a C procedure:

```
int leaf_example (int g, int h, int i, int j)
{
    int f;

    f = (g + h) - (i + j);
    return f;
}
```

What is the compiled MIPS assembly code?

ANSWER

The parameter variables g, h, i, and j correspond to the argument registers \$a0, \$a1, \$a2, and \$a3, and f corresponds to \$s0. The compiled program starts with the label of the procedure:

```
leaf_example:
```

The next step is to save the registers used by the procedure. The C assignment statement in the procedure body is identical to the example on page 79, which uses two temporary registers. Thus, we need to save three registers: \$s0, \$t0, and \$t1. We “push” the old values onto the stack by creating space for three words (12 bytes) on the stack and then store them:

```
addi $sp, $sp, -12      # adjust stack to make room for 3 items
sw  $t1, 8($sp)        # save register $t1 for use afterwards
sw  $t0, 4($sp)        # save register $t0 for use afterwards
sw  $s0, 0($sp)        # save register $s0 for use afterwards
```

Figure 2.10 shows the stack before, during, and after the procedure call.

The next three statements correspond to the body of the procedure, which follows the example on page 79:

```
add $t0,$a0,$a1 # register $t0 contains g + h
add $t1,$a2,$a3 # register $t1 contains i + j
sub $s0,$t0,$t1 # f = $t0 - $t1, which is (g + h)-(i + j)
```

To return the value of f, we copy it into a return value register:

```
add $v0,$s0,$zero # returns f ($v0 = $s0 + 0)
```

Before returning, we restore the three old values of the registers we saved by “popping” them from the stack:

```
lw  $s0, 0($sp) # restore register $s0 for caller
lw  $t0, 4($sp) # restore register $t0 for caller
lw  $t1, 8($sp) # restore register $t1 for caller
addi $sp,$sp,12 # adjust stack to delete 3 items
```

The procedure ends with a jump register using the return address:

```
jr $ra    # jump back to calling routine
```

In the previous example, we used temporary registers and assumed their old values must be saved and restored. To avoid saving and restoring a register whose value is never used, which might happen with a temporary register, MIPS software separates 18 of the registers into two groups:

- \$t0–\$t9: ten temporary registers that are *not* preserved by the callee (called procedure) on a procedure call
- \$s0–\$s7: eight saved registers that must be preserved on a procedure call (if used, the callee saves and restores them)

This simple convention reduces register spilling. In the example above, since the caller does not expect registers \$t0 and \$t1 to be preserved across a procedure call,

we can drop two stores and two loads from the code. We still must save and restore \$s0, since the callee must assume that the caller needs its value.

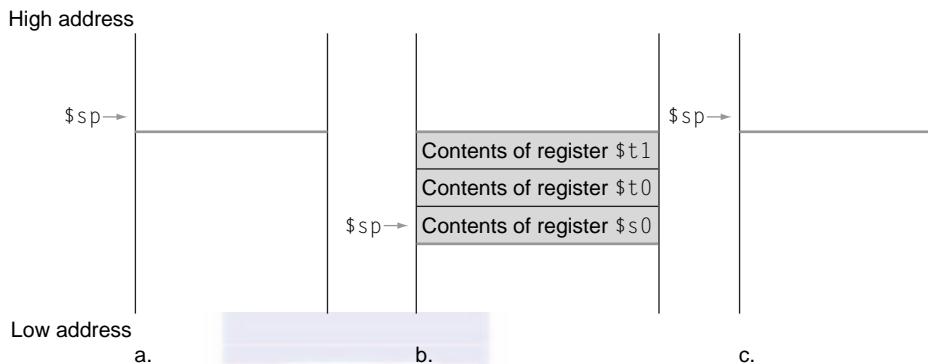


FIGURE 2.10 The values of the stack pointer and the stack (a) before, (b) during, and (c) after the procedure call. The stack pointer always points to the “top” of the stack, or the last word in the stack in this drawing.

Nested Procedures

Procedures that do not call others are called *leaf* procedures. Life would be simple if all procedures were leaf procedures, but they aren’t. Just as a spy might employ other spies as part of a mission, who in turn might use even more spies, so do procedures invoke other procedures. Moreover, recursive procedures even invoke “clones” of themselves. Just as we need to be careful when using registers in procedures, more care must also be taken when invoking nonleaf procedures.

For example, suppose that the main program calls procedure A with an argument of 3, by placing the value 3 into register \$a0 and then using `jal A`. Then suppose that procedure A calls procedure B via `jal B` with an argument of 7, also placed in \$a0. Since A hasn’t finished its task yet, there is a conflict over the use of register \$a0. Similarly, there is a conflict over the return address in register \$ra, since it now has the return address for B. Unless we take steps to prevent the problem, this conflict will eliminate procedure A’s ability to return to its caller.

One solution is to push all the other registers that must be preserved onto the stack, just as we did with the saved registers. The caller pushes any argument registers (\$a0–\$a3) or temporary registers (\$t0–\$t9) that are needed after the call. The callee pushes the return address register \$ra and any saved registers (\$s0–\$s7) used by the callee. The stack pointer \$sp is adjusted to account for the number of registers placed on the stack. Upon the return, the registers are restored from memory and the stack pointer is readjusted.

Compiling a Recursive C Procedure, Showing Nested Procedure Linking

Let's tackle a recursive procedure that calculates factorial:

```
int fact (int n)
{
    if (n < 1) return (1);
        else return (n * fact(n - 1));
}
```

What is the MIPS assembly code?

EXAMPLE

The parameter variable *n* corresponds to the argument register \$a0. The compiled program starts with the label of the procedure and then saves two registers on the stack, the return address and \$a0:

ANSWER

```
fact:
    addi  $sp, $sp, -8  # adjust stack for 2 items
    sw    $ra, 4($sp)   # save the return address
    sw    $a0, 0($sp)   # save the argument n
```

The first time *fact* is called, *sw* saves an address in the program that called *fact*. The next two instructions test whether *n* is less than 1, going to L1 if *n* ≥ 1 .

```
    slti $t0,$a0,1      # test for n < 1
    beq  $t0,$zero,L1   # if n >= 1, go to L1
```

If *n* is less than 1, *fact* returns 1 by putting 1 into a value register: it adds 1 to 0 and places that sum in \$v0. It then pops the two saved values off the stack and jumps to the return address:

```
    addi  $v0,$zero,1 # return 1
    addi  $sp,$sp,8   # pop 2 items off stack
    jr    $ra          # return to caller
```

Before popping two items off the stack, we could have loaded \$a0 and \$ra. Since \$a0 and \$ra don't change when *n* is less than 1, we skip those instructions.

If *n* is not less than 1, the argument *n* is decremented and then *fact* is called again with the decremented value:

```
L1: addi $a0,$a0,-1  # n >= 1: argument gets (n - 1)
    jal  fact           # call fact with (n - 1)
```

The next instruction is where `fact` returns. Now the old return address and old argument are restored, along with the stack pointer:

```
lw    $a0, 0($sp)    # return from jal: restore argument n
lw    $ra, 4($sp)    # restore the return address
addi $sp, $sp, 8     # adjust stack pointer to pop 2 items
```

Next, the value register `$v0` gets the product of old argument `$a0` and the current value of the value register. We assume a multiply instruction is available, even though it is not covered until Chapter 3:

```
mul $v0,$a0,$v0    # return n * fact (n - 1)
```

Finally, `fact` jumps again to the return address:

```
jr    $ra             # return to the caller
```

Hardware/ Software Interface

global pointer The register that is reserved to point to the static area.

A C variable is generally a location in storage, and its interpretation depends both on its *type* and *storage class*. Examples include integers and characters (see Section 2.9). C has two storage classes: *automatic* and *static*. Automatic variables are local to a procedure and are discarded when the procedure exits. Static variables exist across exits from and entries to procedures. C variables declared outside all procedures are considered static, as are any variables declared using the keyword *static*. The rest are automatic. To simplify access to static data, MIPS software reserves another register, called the **global pointer**, or `$gp`.

Figure 2.11 summarizes what is preserved across a procedure call. Note that several schemes preserve the stack, guaranteeing that the caller will get the same data back on a load from the stack as it stored onto the stack. The stack above `$sp` is preserved simply by making sure the callee does not write above `$sp`; `$sp` is itself preserved by the callee adding exactly the same amount that was subtracted from it; and the other registers are preserved by saving them on the stack (if they are used) and restoring them from there.

Preserved	Not preserved
Saved registers: <code>\$s0-\$s7</code>	Temporary registers: <code>\$t0-\$t9</code>
Stack pointer register : <code>\$sp</code>	Argument register s: <code>\$a0-\$a3</code>
Return address register : <code>\$ra</code>	Return value register s: <code>\$v0-\$v1</code>
Stack above the stack pointer	Stack below the stack pointer

FIGURE 2.11 What is and what is not preserved across a procedure call. If the software relies on the frame pointer register or on the global pointer register, discussed in the following subsections, they are also preserved.

Allocating Space for New Data on the Stack

The final complexity is that the stack is also used to store variables that are local to the procedure but do not fit in registers, such as local arrays or structures. The segment of the stack containing a procedure's saved registers and local variables is called a **procedure frame** or **activation record**. Figure 2.12 shows the state of the stack before, during, and after the procedure call.

Some MIPS software uses a **frame pointer** ($\$fp$) to point to the first word of the frame of a procedure. A stack pointer might change during the procedure, and so references to a local variable in memory might have different offsets depending on where they are in the procedure, making the procedure harder to understand. Alternatively, a frame pointer offers a stable base register within a procedure for local memory-references. Note that an activation record appears on the stack whether or not an explicit frame pointer is used. We've been avoiding using $\$fp$ by avoiding changes to $\$sp$ within a procedure: in our examples, the stack is adjusted only on entry and exit of the procedure.

procedure frame Also called activation record. The segment of the stack containing a procedure's saved registers and local variables.

frame pointer A value denoting the location of the saved registers and local variables for a given procedure.

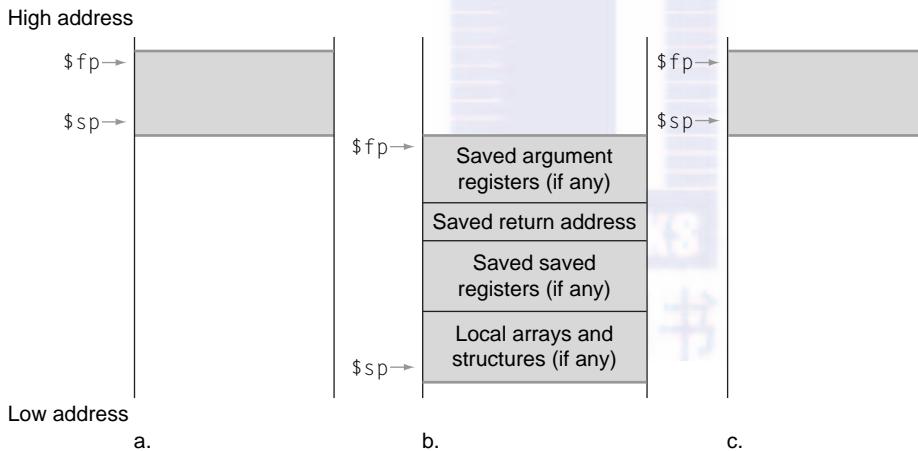


FIGURE 2.12 Illustration of the stack allocation (a) before, (b) during, and (c) after the procedure call. The frame pointer ($\$fp$) points to the first word of the frame, often a saved argument register, and the stack pointer ($\$sp$) points to the top of the stack. The stack is adjusted to make room for all the saved registers and any memory-resident local variables. Since the stack pointer may change during program execution, it's easier for programmers to reference variables via the stable frame pointer, although it could be done just with the stack pointer and a little address arithmetic. If there are no local variables on the stack within a procedure, the compiler will save time by *not* setting and restoring the frame pointer. When a frame pointer is used, it is initialized using the address in $\$sp$ on a call, and $\$sp$ is restored using $\$fp$. This information is also found in Column 4 of the MIPS Reference Data Card at the front of this book.

Allocating Space for New Data on the Heap

In addition to automatic variables that are local to procedures, C programmers need space in memory for static variables and for dynamic data structures. Figure 2.13 shows the MIPS convention for allocation of memory. The stack starts in the high end of memory and grows down. The first part of the low end of memory is reserved, followed by the home of the MIPS machine code, traditionally called the **text segment**. Above the code is the **static data segment**, which is the place for constants and other static variables. Although arrays tend to be a fixed length and thus are a good match to the static data segment, data structures like linked lists tend to grow and shrink during their lifetimes. The segment for such data structures is traditionally called the **heap**, and it is placed next in memory. Note that this allocation allows the stack and heap to grow toward each other, thereby allowing the efficient use of memory as the two segments wax and wane.

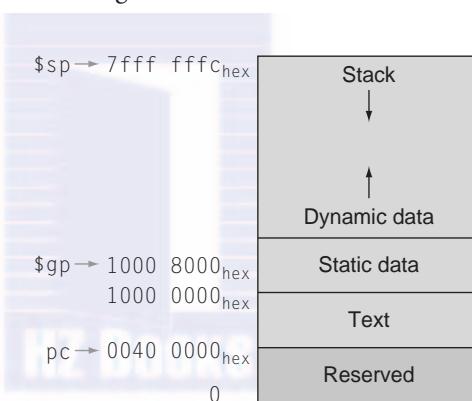


FIGURE 2.13 The MIPS memory allocation for program and data. These addresses are only a software convention, and not part of the MIPS architecture. The stack pointer is initialized to 7fff fffC_{hex} and grows down toward the data segment. At the other end, the program code (“text”) starts at 0040 0000_{hex}. The static data starts at 1000 0000_{hex}. Dynamic data, allocated by `malloc` in C and by `new` in Java, is next. It grows up toward the stack in an area called the heap. The global pointer, \$gp, is set to an address to make it easy to access data. It is initialized to 1000 8000_{hex} so that it can access from 1000 0000_{hex} to 1000 ffff_{hex} using the positive and negative 16-bit offsets from \$gp. This information is also found in Column 4 of the MIPS Reference Data Card at the front of this book.

C allocates and frees space on the heap with explicit functions. `malloc()` allocates space on the heap and returns a pointer to it, and `free()` releases space on the heap to which the pointer points. Memory allocation is controlled by programs in C, and it is the source of many common and difficult bugs. Forgetting to free space leads to a “memory leak,” which eventually uses up so much memory that the operating system may crash. Freeing space too early leads to “dangling pointers,” which can cause pointers to point to things that the program never intended. Java uses automatic memory allocation and garbage collection just to avoid such bugs.

text segment The segment of a UNIX object file that contains the machine language code for routines in the source file.

Figure 2.14 summarizes the register conventions for the MIPS assembly language.

Name	Register number	Usage	Preserved on call?
\$zero	0	The constant value 0	n.a.
\$v0-\$v1	2-3	Values for results and expression evaluation	no
\$a0-\$a3	4-7	Arguments	no
\$t0-\$t7	8-15	Temporaries	no
\$s0-\$s7	16-23	Saved	yes
\$t8-\$t9	24-25	More temporaries	no
\$gp	28	Global pointer	yes
\$sp	29	Stack pointer	yes
\$fp	30	Frame pointer	yes
\$ra	31	Return address	yes

FIGURE 2.14 MIPS register conventions. Register 1, called \$at, is reserved for the assembler (see Section 2.12), and registers 26–27, called \$k0–\$k1, are reserved for the operating system. This information is also found in Column 2 of the MIPS Reference Data Card at the front of this book.

Elaboration: What if there are more than four parameters? The MIPS convention is to place the extra parameters on the stack just above the frame pointer. The procedure then expects the first four parameters to be in registers \$a0 through \$a3 and the rest in memory, addressable via the frame pointer.

As mentioned in the caption of Figure 2.12, the frame pointer is convenient because all references to variables in the stack within a procedure will have the same offset. The frame pointer is not necessary, however. The GNU MIPS C compiler uses a frame pointer, but the C compiler from MIPS does not; it treats register 30 as another save register (\$s8).

Elaboration: Some recursive procedures can be implemented iteratively without using recursion. Iteration can significantly improve performance by removing the overhead associated with procedure calls. For example, consider a procedure used to accumulate a sum:

```
int sum (int n, int acc) {
    if (n > 0)
        return sum(n - 1, acc + n);
    else
        return acc;
}
```

Consider the procedure call `sum(3,0)`. This will result in recursive calls to `sum(2,3)`, `sum(1,5)`, and `sum(0,6)`, and then the result 6 will be returned four times. This recursive call of `sum` is referred to as a *tail call*, and this example use of tail recursion can be implemented very efficiently (assume `$a0 = n` and `$a1 = acc`):

```
sum: slti$a0,1          # test if n <= 0
     beq$a0, $zero, sum_exit # go to sum_exit if n <= 0
     add$a1, $a1, $a0        # add n to acc
```

```

addi$a0, $a0, -1      # subtract 1 from n
j sum                  # go to sum
sum_exit:
add$v0, $a1, $zero    # return value acc
jr $ra                 # return to caller

```

- Check Yourself** Which of the following statements about C and Java are generally true?
1. C programmers manage data explicitly, while it's automatic in Java.
 2. C leads to more pointer bugs and memory leak bugs than does Java.

*!(@|= > (wow open
tab at bar is great)*

Fourth line of the keyboard poem “Hatless Atlas,” 1991 (some give names to ASCII characters: “!” is “wow,” “(” is open, “)” is bar, and so on).

2.9

Communicating with People

Computers were invented to crunch numbers, but as soon as they became commercially viable they were used to process text. Most computers today offer 8-bit bytes to represent characters, with the American Standard Code for Information Interchange (ASCII) being the representation that nearly everyone follows. Figure 2.15 summarizes ASCII.

ASCII value	Character										
32	space	48	0	64	@	80	P	96	`	112	p
33	!	49	1	65	A	81	Q	97	a	113	q
34	"	50	2	66	B	82	R	98	b	114	r
35	#	51	3	67	C	83	S	99	c	115	s
36	\$	52	4	68	D	84	T	100	d	116	t
37	%	53	5	69	E	85	U	101	e	117	u
38	&	54	6	70	F	86	V	102	f	118	v
39	'	55	7	71	G	87	W	103	g	119	w
40	(56	8	72	H	88	X	104	h	120	x
41)	57	9	73	I	89	Y	105	i	121	y
42	*	58	:	74	J	90	Z	106	j	122	z
43	+	59	;	75	K	91	[107	k	123	{
44	,	60	<	76	L	92	\	108	l	124	
45	-	61	=	77	M	93]	109	m	125	}
46	.	62	>	78	N	94	^	110	n	126	~
47	/	63	?	79	O	95	-	111	o	127	DEL

FIGURE 2.15 ASCII representation of characters. Note that upper- and lowercase letters differ by exactly 32; this observation can lead to shortcuts in checking or changing uppercase and lowercase. Values not shown include formatting characters. For example, 8 represents a backspace, 9 represents a tab character, and 13 a carriage return. Another useful value is 0 for null, the value the programming language C uses to mark the end of a string. This information is also found in Column 3 of the MIPS Reference Data Card at the front of this book.

Base 2 is not natural to human beings; we have 10 fingers and so find base 10 natural. Why didn't computers use decimal? In fact, the first commercial computer *did* offer decimal arithmetic. The problem was that the computer still used on and off signals, so a decimal digit was simply represented by several binary digits. Decimal proved so inefficient that subsequent computers reverted to all binary, converting to base 10 only for the relatively infrequent input/output events.

Hardware/ Software Interface

ASCII versus Binary Numbers

We could represent numbers as strings of ASCII digits instead of as integers. How much does storage increase if the number 1 billion is represented in ASCII versus a 32-bit integer?

EXAMPLE

One billion is 1,000,000,000, so it would take 10 ASCII digits, each 8 bits long. Thus the storage expansion would be $(10 \times 8)/32$ or 2.5. In addition to the expansion in storage, the hardware to add, subtract, multiply, and divide such decimal numbers is difficult. Such difficulties explain why computing professionals are raised to believe that binary is natural and that the occasional decimal computer is bizarre.

ANSWER

A series of instructions can extract a byte from a word, so load word and store word are sufficient for transferring bytes as well as words. Because of the popularity of text in some programs, however, MIPS provides instructions to move bytes. Load byte (`lb`) loads a byte from memory, placing it in the rightmost 8 bits of a register. Store byte (`sb`) takes a byte from the rightmost 8 bits of a register and writes it to memory. Thus, we copy a byte with the sequence

```
lb $t0,0($sp)          # Read byte from source
sb $t0,0($gp)          # Write byte to destination
```

Hardware/ Software Interface

Signed versus unsigned applies to loads as well as to arithmetic. The *function* of a signed load is to copy the sign repeatedly to fill the rest of the register—called *sign extension*—but its *purpose* is to place a correct representation of the number within that register. Unsigned loads simply fill with 0s to the left of the data, since the number represented by the bit pattern is unsigned.

When loading a 32-bit word into a 32-bit register, the point is moot; signed and unsigned loads are identical. MIPS does offer two flavors of byte loads: *load byte* (`lb`) treats the byte as a signed number and thus sign-extends to fill the 24 left-most bits of the register, while *load byte unsigned* (`lbu`) works with unsigned integers. Since C programs almost always use bytes to represent characters rather than consider bytes as very short signed integers, `lbu` is used practically exclusively for byte loads.

Characters are normally combined into strings, which have a variable number of characters. There are three choices for representing a string: (1) the first position of the string is reserved to give the length of a string, (2) an accompanying variable has the length of the string (as in a structure), or (3) the last position of a string is indicated by a character used to mark the end of a string. C uses the third choice, terminating a string with a byte whose value is 0 (named null in ASCII). Thus, the string “Cal” is represented in C by the following 4 bytes, shown as decimal numbers: 67, 97, 108, 0. (As we shall see, Java uses the first option.)

EXAMPLE

Compiling a String Copy Procedure, Showing How to Use C Strings

The procedure `strcpy` copies string `y` to string `x` using the null byte termination convention of C:

```
void strcpy (char x[], char y[])
{
    int i;

    i = 0;
    while ((x[i] = y[i]) != '\0') /* copy & test byte */
        i += 1;
}
```

What is the MIPS assembly code?

Below is the basic MIPS assembly code segment. Assume that base addresses for arrays *x* and *y* are found in \$a0 and \$a1, while *i* is in \$s0. strcpy adjusts the stack pointer and then saves the saved register \$s0 on the stack:

ANSWER

```
strcpy:
    addi   $sp,$sp,-4    # adjust stack for 1 more item
    sw     $s0, 0($sp)  # save $s0
```

To initialize *i* to 0, the next instruction sets \$s0 to 0 by adding 0 to 0 and placing that sum in \$s0:

```
add   $s0,$zero,$zero # i = 0 + 0
```

This is the beginning of the loop. The address of *y[i]* is first formed by adding *i* to *y[]*:

```
L1: add   $t1,$s0,$a1  # address of y[i] in $t1
```

Note that we don't have to multiply *i* by 4 since *y* is an array of *bytes* and not of words, as in prior examples.

To load the character in *y[i]*, we use load byte unsigned, which puts the character into \$t2:

```
lbu   $t2, 0($t1)  # $t2 = y[i]
```

A similar address calculation puts the address of *x[i]* in \$t3, and then the character in \$t2 is stored at that address.

```
add   $t3,$s0,$a0  # address of x[i] in $t3
sb    $t2, 0($t3)  # x[i] = y[i]
```

Next, we exit the loop if the character was 0. That is, we exit if it is the last character of the string:

```
beq   $t2,$zero,L2 # if y[i] == 0, go to L2
```

If not, we increment *i* and loop back:

```
addi  $s0, $s0,1   # i = i + 1
j     L1           # go to L1
```

If we don't loop back, it was the last character of the string; we restore \$s0 and the stack pointer, and then return.

```
L2: lw      $s0, 0($sp) # y[i] == 0: end of string. Re-
    store old $s0

    addi   $sp,$sp,4    # pop 1 word off stack
    jr     $ra           # return
```

String copies usually use pointers instead of arrays in C to avoid the operations on *i* in the code above. See Section 2.14 for an explanation of arrays versus pointers.

Since the procedure `strcpy` above is a leaf procedure, the compiler could allocate *i* to a temporary register and avoid saving and restoring \$s0. Hence, instead of thinking of the \$t registers as being just for temporaries, we can think of them as registers that the callee should use whenever convenient. When a compiler finds a leaf procedure, it exhausts all temporary registers before using registers it must save.

Characters and Strings in Java

Unicode is a universal encoding of the alphabets of most human languages. Figure 2.16 is a list of Unicode alphabets; there are almost as many *alphabets* in Unicode as there are useful *symbols* in ASCII. To be more inclusive, Java uses Unicode for characters. By default, it uses 16 bits to represent a character.

The MIPS instruction set has explicit instructions to load and store such 16-bit quantities, called *halfwords*. Load half (lh) loads a halfword from memory, placing it in the rightmost 16 bits of a register. Like load byte, *load half* (lh) treats the halfword as a signed number and thus sign-extends to fill the 16 leftmost bits of the register, while *load halfword unsigned* (lhu) works with unsigned integers. Thus, lhu is the more popular of the two. Store half (sh) takes a halfword from the rightmost 16 bits of a register and writes it to memory. We copy a halfword with the sequence

```
lhu $t0,0($sp) # Read halfword (16 bits) from source
sh $t0,0($gp)  # Write halfword (16 bits) to destination
```

Strings are a standard Java class with special built-in support and predefined methods for concatenation, comparison, and conversion. Unlike C, Java includes a word that gives the length of the string, similar to Java arrays.

Elaboration: MIPS software tries to keep the stack aligned to word addresses, allowing the program to always use lw and sw (which must be aligned) to access the stack. This convention means that a char variable allocated on the stack occupies 4 bytes, even though it needs less. However, a C string variable or an array of bytes will pack 4 bytes per word, and a Java string variable or array of shorts packs 2 halfwords per word.

Latin	Malayalam	Tagbanwa	General Punctuation
Greek	Sinhala	Khmer	Spacing Modifier Letters
Cyrillic	Thai	Mongolian	Currency Symbols
Armenian	Lao	Limbu	Combining Diacritical Marks
Hebrew	Tibetan	Tai Le	Combining Marks for Symbols
Arabic	Myanmar	Kangxi Radicals	Superscripts and Subscripts
Syriac	Georgian	Hiragana	Number Forms
Thaana	Hangul Jamo	Katakana	Mathematical Operators
Devanagari	Ethiopic	Bopomofo	Mathematical Alphanumeric Symbols
Bengali	Cherokee	Kanbun	Braille Patterns
Gurmukhi	Unified Canadian Aboriginal Syllabic	Shavian	Optical Character Recognition
Gujarati	Ogham	Osmanya	Byzantine Musical Symbols
Oriya	Runic	Cypriot Syllabary	Musical Symbols
Tamil	Tagalog	Tai Xuan Jing Symbols	Arrows
Telugu	Hanunoo	Yijing Hexagram Symbols	Box Drawing
Kannada	Buhid	Aegean Numbers	Geometric Shapes

FIGURE 2.16 Example alphabets in Unicode. Unicode version 4.0 has more than 160 “blocks,” which is their name for a collection of symbols. Each block is a multiple of 16. For example, Greek starts at 0370_{hex} and Cyrillic at 0400_{hex} . The first three columns show 48 blocks that correspond to human languages in roughly Unicode numerical order. The last column has 16 blocks that are multilingual and are not in order. A 16-bit encoding, called UTF-16, is the default. A variable-length encoding, called UTF-8, keeps the ASCII subset as eight bits and uses 16–32 bits for the other characters. UTF-32 uses 32 bits per character. To learn more, see www.unicode.org.

I. Which of the following statements about characters and strings in C and Java are true?

1. A string in C takes about half the memory as the same string in Java.
2. Strings are just an informal name for single-dimension arrays of characters in C and Java.
3. Strings in C and Java use null (0) to mark the end of a string.
4. Operations on strings, like length, are faster in C than in Java.

Check Yourself

II. Which type of variable that can contain $1,000,000,000_{\text{ten}}$ takes the most memory space?

1. int in C
2. string in C
3. string in Java

2.10**MIPS Addressing for 32-Bit Immediate
and Addresses**

Although keeping all MIPS instructions 32 bits long simplifies the hardware, there are times where it would be convenient to have a 32-bit constant or 32-bit address. This section starts with the general solution for large constants, and then shows the optimizations for instruction addresses used in branches and jumps.

32-Bit Immediate Operands

Although constants are frequently short and fit into the 16-bit field, sometimes they are bigger. The MIPS instruction set includes the instruction *load upper immediate* (*lui*) specifically to set the upper 16 bits of a constant in a register, allowing a subsequent instruction to specify the lower 16 bits of the constant. Figure 2.17 shows the operation of *lui*.

EXAMPLE**Loading a 32-Bit Constant**

What is the MIPS assembly code to load this 32-bit constant into register \$s0?

0000 0000 0011 1101 0000 1001 0000 0000

ANSWER

First, we would load the upper 16 bits, which is 61 in decimal, using *lui*:

lui \$s0, 61 # 61 decimal = 0000 0000 0011 1101 binary

The value of register \$s0 afterward is

0000 0000 0011 1101 0000 0000 0000 0000

The next step is to insert the lower 16 bits, whose decimal value is 2304:

ori \$s0, \$s0, 2304 # 2304 decimal = 0000 1001 0000 0000

The final value in register \$s0 is the desired value:

0000 0000 0011 1101 0000 1001 0000 0000

The machine language version of `lui $t0, 255` # \$t0 is register 8:

001111	00000	01000	0000 0000 1111 1111
--------	-------	-------	---------------------

Contents of register \$t0 after executing `lui $t0, 255`:

0000 0000 1111 1111	0000 0000 0000 0000
---------------------	---------------------

FIGURE 2.17 The effect of the `lui` instruction. The instruction `lui` transfers the 16-bit immediate constant field value into the leftmost 16 bits of the register, filling the lower 16 bits with 0s.

Hardware/ Software Interface

Either the compiler or the assembler must break large constants into pieces and then reassemble them into a register. As you might expect, the immediate field's size restriction may be a problem for memory addresses in loads and stores as well as for constants in immediate instructions. If this job falls to the assembler, as it does for MIPS software, then the assembler must have a temporary register available in which to create the long values. This is a reason for the register `$at`, which is reserved for the assembler.

Hence, the symbolic representation of the MIPS machine language is no longer limited by the hardware, but by whatever the creator of an assembler chooses to include (see Section 2.12). We stick close to the hardware to explain the architecture of the computer, noting when we use the enhanced language of the assembler that is not found in the processor.

Elaboration: Creating 32-bit constants needs care. The instruction `addi` copies the leftmost bit of the 16-bit immediate field of the instruction into the upper 16 bits of a word. *Logical or immediate* from Section 2.6 loads 0s into the upper 16 bits and hence is used by the assembler in conjunction with `lui` to create 32-bit constants.

Addressing in Branches and Jumps

The MIPS jump instructions have the simplest addressing. They use the final MIPS instruction format, called the *J-type*, which consists of 6 bits for the operation field and the rest of the bits for the address field. Thus,

`j 10000 # go to location 10000`

could be assembled into this format (it's actually a bit more complicated, as we will see):

2	10000
6 bits	26 bits

where the value of the jump opcode is 2 and the jump address is 10000.

Unlike the jump instruction, the conditional branch instruction must specify two operands in addition to the branch address. Thus,

```
bne $s0,$s1,Exit # go to Exit if $s0 ≠ $s1
```

is assembled into this instruction, leaving only 16 bits for the branch address:

5	16	17	Exit
6 bits	5 bits	5 bits	16 bits

If addresses of the program had to fit in this 16-bit field, it would mean that no program could be bigger than 2^{16} , which is far too small to be a realistic option today. An alternative would be to specify a register that would always be added to the branch address, so that a branch instruction would calculate the following:

$$\text{Program counter} = \text{Register} + \text{Branch address}$$

This sum allows the program to be as large as 2^{32} and still be able to use conditional branches, solving the branch address size problem. Then the question is, which register?

The answer comes from seeing how conditional branches are used. Conditional branches are found in loops and in *if* statements, so they tend to branch to a nearby instruction. For example, about half of all conditional branches in SPEC benchmarks go to locations less than 16 instructions away. Since the program counter (PC) contains the address of the current instruction, we can branch within $\pm 2^{15}$ words of the current instruction if we use the PC as the register to be added to the address. Almost all loops and *if* statements are much smaller than 2^{16} words, so the PC is the ideal choice.

This form of branch addressing is called **PC-relative addressing**. As we shall see in Chapter 4, it is convenient for the hardware to increment the PC early to point to the next instruction. Hence, the MIPS address is actually relative to the address of the following instruction ($\text{PC} + 4$) as opposed to the current instruction (PC).

Like most recent computers, MIPS uses PC-relative addressing for all conditional branches, because the destination of these instructions is likely to be close to the branch. On the other hand, jump-and-link instructions invoke procedures that have no reason to be near the call, so they normally use other forms of addressing. Hence, the MIPS architecture offers long addresses for procedure calls by using the J-type format for both jump and jump-and-link instructions.

Since all MIPS instructions are 4 bytes long, MIPS stretches the distance of the branch by having PC-relative addressing refer to the number of *words* to the next instruction instead of the number of bytes. Thus, the 16-bit field can branch four

PC-relative addressing
An addressing regime in which the address is the sum of the program counter (PC) and a constant in the instruction.

times as far by interpreting the field as a relative word address rather than as a relative byte address. Similarly, the 26-bit field in jump instructions is also a word address, meaning that it represents a 28-bit byte address.

Elaboration: Since the PC is 32 bits, 4 bits must come from somewhere else for jumps. The MIPS jump instruction replaces only the lower 28 bits of the PC, leaving the upper 4 bits of the PC unchanged. The loader and linker (Section 2.12) must be careful to avoid placing a program across an address boundary of 256 MB (64 million instructions); otherwise, a jump must be replaced by a jump register instruction preceded by other instructions to load the full 32-bit address into a register.

Showing Branch Offset in Machine Language

The *while* loop on page 107–108 was compiled into this MIPS assembler code:

```

Loop: sll    $t1,$s3,2  # Temp reg $t1 = 4 * i
      add $t1,$t1,$s6  # $t1 = address of save[i]
      lw   $t0,0($t1)   # Temp reg $t0 = save[i]
      bne $t0,$s5, Exit # go to Exit if save[i] ≠ k
      addi $s3,$s3,1    # i = i + 1
      j    Loop        # go to Loop
Exit:

```

EXAMPLE

If we assume we place the loop starting at location 80000 in memory, what is the MIPS machine code for this loop?

The assembled instructions and their addresses are:

ANSWER

80000	0	0	19	9	2	0
80004	0	9	22	9	0	32
80008	35	9	8		0	
80012	5	8	21		2	
80016	8	19	19		1	
80020	2			20000		
80024	...					

Remember that MIPS instructions have byte addresses, so addresses of sequential words differ by 4, the number of bytes in a word. The bne instruction on the fourth line adds 2 words or 8 bytes to the address of the *following* instruction (80016), specifying the branch destination relative to that following instruction ($8 + 80016$) instead of relative to the branch instruction ($12 + 80012$) or using the full destination address (80024). The jump instruction on the last line does use the full address ($20000 \times 4 = 80000$), corresponding to the label Loop.

Hardware/ Software Interface

Most conditional branches are to a nearby location, but occasionally they branch far away, farther than can be represented in the 16 bits of the conditional branch instruction. The assembler comes to the rescue just as it did with large addresses or constants: it inserts an unconditional jump to the branch target, and inverts the condition so that the branch decides whether to skip the jump.

EXAMPLE

ANSWER

Branching Far Away

Given a branch on register \$s0 being equal to register \$s1,

```
beq    $s0, $s1, L1
```

replace it by a pair of instructions that offers a much greater branching distance.

These instructions replace the short-address conditional branch:

```
bne    $s0, $s1, L2
```

```
j      L1
```

L2:

MIPS Addressing Mode Summary

addressing mode One of several addressing regimes delimited by their varied use of operands and/or addresses.

Multiple forms of addressing are generically called **addressing modes**. Figure 2.18 shows how operands are identified for each addressing mode. The MIPS addressing modes are the following:

1. *Immediate addressing*, where the operand is a constant within the instruction itself
2. *Register addressing*, where the operand is a register

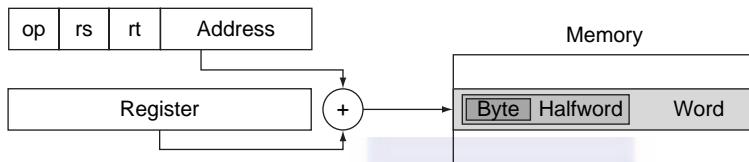
1. Immediate addressing



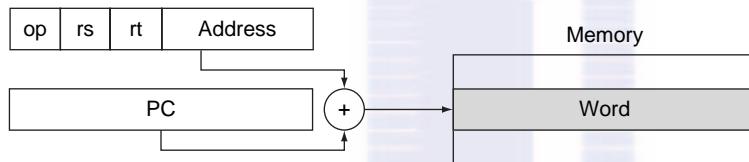
2. Register addressing



3. Base addressing



4. PC-relative addressing



5. Pseudodirect addressing

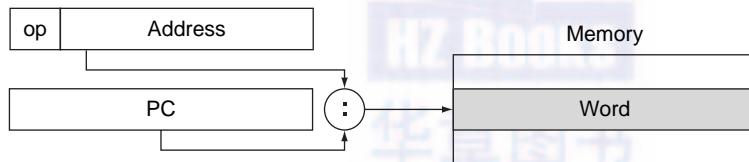


FIGURE 2.18 Illustration of the five MIPS addressing modes. The operands are shaded in color. The operand of mode 3 is in memory, whereas the operand for mode 2 is a register. Note that versions of load and store access bytes, halfwords, or words. For mode 1, the operand is 16 bits of the instruction itself. Modes 4 and 5 address instructions in memory, with mode 4 adding a 16-bit address shifted left 2 bits to the PC and mode 5 concatenating a 26-bit address shifted left 2 bits with the 4 upper bits of the PC.

3. *Base or displacement addressing*, where the operand is at the memory location whose address is the sum of a register and a constant in the instruction
4. *PC-relative addressing*, where the branch address is the sum of the PC and a constant in the instruction
5. *Pseudodirect addressing*, where the jump address is the 26 bits of the instruction concatenated with the upper bits of the PC

Hardware/ Software Interface

Although we show MIPS as having 32-bit addresses, nearly all microprocessors (including MIPS) have 64-bit address extensions (see  Appendix E). These extensions were in response to the needs of software for larger programs. The process of instruction set extension allows architectures to expand in such a way that is able to move software compatibly upward to the next generation of architecture.

Note that a single operation can use more than one addressing mode. Add, for example, uses both immediate (addi) and register (add) addressing.

Decoding Machine Language

Sometimes you are forced to reverse-engineer machine language to create the original assembly language. One example is when looking at “core dump.” Figure 2.19 shows the MIPS encoding of the fields for the MIPS machine language. This figure helps when translating by hand between assembly language and machine language.

EXAMPLE

ANSWER

Decoding Machine Code

What is the assembly language statement corresponding to this machine instruction?

00af8020hex

The first step in converting hexadecimal to binary is to find the op fields:

(Bits: 31 28 26)	5 2 0)
0000 0000 1010 1111 1000 0000 0010 0000	

We look at the op field to determine the operation. Referring to Figure 2.19, when bits 31–29 are 000 and bits 28–26 are 000, it is an R-format instruction. Let’s reformat the binary instruction into R-format fields, listed in Figure 2.20:

op	rs	rt	rd	shamt	funct
000000	00101	01111	10000	00000	100000

The bottom portion of Figure 2.19 determines the operation of an R-format instruction. In this case, bits 5–3 are 100 and bits 2–0 are 000, which means this binary pattern represents an add instruction.

We decode the rest of the instruction by looking at the field values. The decimal values are 5 for the rs field, 15 for rt, and 16 for rd (shamt is unused). Figure 2.14 shows that these numbers represent registers \$a1, \$t7, and \$s0. Now we can reveal the assembly instruction:

add \$s0,\$a1,\$t7

op(31:26)								
28-26 31-29	0(000)	1(001)	2(010)	3(011)	4(100)	5(101)	6(110)	7(111)
0(000)	R-format	Bltz/gez	jump	jump & link	branch eq	branch ne	blez	bgtz
1(001)	add immediate	addiu	set less than imm.	set less than imm. unsigned	andi	ori	xori	load upper immediate
2(010)	TLB	F1Pt						
3(011)								
4(100)	load byte	load half	lw1	load word	load byte unsigned	load half unsigned	lw1r	
5(101)	store byte	store half	sw1	store word			swr	
6(110)	load linked word	lwcl						
7(111)	store cond. word	swcl						

op(31:26)=010000 (TLB), rs(25:21)								
23-21 25-24	0(000)	1(001)	2(010)	3(011)	4(100)	5(101)	6(110)	7(111)
0(00)	mfc0		cfc0		mtc0		ctc0	
1(01)								
2(10)								
3(11)								

op(31:26)=000000 (R-format), funct(5:0)								
2-0 5-3	0(000)	1(001)	2(010)	3(011)	4(100)	5(101)	6(110)	7(111)
0(000)	shift left logical		shift right logical	sra	sllv		srlv	sraw
1(001)	jump register	jalr			syscall	break		
2(010)	mfhi	mthi	mflo	mtlo				
3(011)	mult	multu	div	divu				
4(100)	add	addu	subtract	subu	and	or	xor	not or (nor)
5(101)			set l.t.	set l.t. unsigned				
6(110)								
7(111)								

FIGURE 2.19 MIPS instruction encoding. This notation gives the value of a field by row and by column. For example, the top portion of the figure shows load word in row number 4 (100_{two} for bits 31–29 of the instruction) and column number 3 (011_{two} for bits 28–26 of the instruction), so the corresponding value of the op field (bits 31–26) is 100011_{two}. Underscore means the field is used elsewhere. For example, R-format in row 0 and column 0 (op = 000000_{two}) is defined in the bottom part of the figure. Hence, subtract in row 4 and column 2 of the bottom section means that the funct field (bits 5–0) of the instruction is 100010_{two} and the op field (bits 31–26) is 000000_{two}. The floating point value in row 2, column 1 is defined in Figure 3.18 in Chapter 3. Bltz/gez is the opcode for four instructions found in Appendix B: bltz, bgez, bltzal, and bgezal. This chapter describes instructions given in full name using color, while Chapter 3 describes instructions given in mnemonics using color. Appendix B covers all instructions.

Name	Fields						Comments
Field size	6 bits	5 bits	5 bits	5 bits	5 bits	6 bits	All MIPS instructions are 32 bits long
R-format	op	rs	rt	rd	shamt	funct	Arithmetic instruction format
I-format op		rs	rt	address/immediate			Transfer, branch, imm. format
J-format	op	target address					Jump instruction format

FIGURE 2.20 MIPS instruction formats.

Figure 2.20 shows all the MIPS instruction formats. Figure 2.1 on page 78 shows the MIPS assembly language revealed in this chapter. The remaining hidden portion of MIPS instructions deals mainly with arithmetic and real numbers, which are covered in the next chapter.

Check Yourself

- What is the range of addresses for conditional branches in MIPS ($K = 1024$)?
 - Addresses between 0 and $64K - 1$
 - Addresses between 0 and $256K - 1$
 - Addresses up to about $32K$ before the branch to about $32K$ after
 - Addresses up to about $128K$ before the branch to about $128K$ after
- What is the range of addresses for jump and jump and link in MIPS ($M = 1024K$)?
 - Addresses between 0 and $64M - 1$
 - Addresses between 0 and $256M - 1$
 - Addresses up to about $32M$ before the branch to about $32M$ after
 - Addresses up to about $128M$ before the branch to about $128M$ after
 - Anywhere within a block of $64M$ addresses where the PC supplies the upper 6 bits
 - Anywhere within a block of $256M$ addresses where the PC supplies the upper 4 bits
- What is the MIPS assembly language instruction corresponding to the machine instruction with the value $0000\ 0000_{hex}$?
 - j
 - R-format
 - addi
 - sll
 - mfc0
 - Undefined opcode: there is no legal instruction that corresponds to 0

2.11

Parallelism and Instructions: Synchronization

Parallel execution is easier when tasks are independent, but often they need to cooperate. Cooperation usually means some tasks are writing new values that others must read. To know when a task is finished writing so that it is safe for another to read, the tasks need to synchronize. If they don't synchronize, there is a danger of a **data race**, where the results of the program can change depending on how events happen to occur.

For example, recall the analogy of the eight reporters writing a story on page 43 of Chapter 1. Suppose one reporter needs to read all the prior sections before writing a conclusion. Hence, he must know when the other reporters have finished their sections, so that he or she need not worry about them being changed afterwards. That is, they had better synchronize the writing and reading of each section so that the conclusion will be consistent with what is printed in the prior sections.

In computing, synchronization mechanisms are typically built with user-level software routines that rely on hardware-supplied synchronization instructions. In this section, we focus on the implementation of *lock* and *unlock* synchronization operations. Lock and unlock can be used straightforwardly to create regions where only a single processor can operate, called *mutual exclusion*, as well as to implement more complex synchronization mechanisms.

The critical ability we require to implement synchronization in a multiprocessor is a set of hardware primitives with the ability to *atomically* read and modify a memory location. That is, nothing else can interpose itself between the read and the write of the memory location. Without such a capability, the cost of building basic synchronization primitives will be too high and will increase as the processor count increases.

There are a number of alternative formulations of the basic hardware primitives, all of which provide the ability to atomically read and modify a location, together with some way to tell if the read and write were performed atomically. In general, architects do not expect users to employ the basic hardware primitives, but instead expect that the primitives will be used by system programmers to build a synchronization library, a process that is often complex and tricky.

Let's start with one such hardware primitive and show how it can be used to build a basic synchronization primitive. One typical operation for building synchronization operations is the *atomic exchange* or *atomic swap*, which interchanges a value in a register for a value in memory.

To see how to use this to build a basic synchronization primitive, assume that we want to build a simple lock where the value 0 is used to indicate that the lock is free and 1 is used to indicate that the lock is unavailable. A processor tries to set the lock by doing an exchange of 1, which is in a register, with the memory address corresponding to the lock. The value returned from the exchange instruction is 1 if some other processor had already claimed access and 0 otherwise. In the latter case, the value is also changed to 1, preventing any competing exchange in another processor from also retrieving a 0.

data race Two memory accesses form a data race if they are from different threads to same location, at least one is a write, and they occur one after another.

For example, consider two processors that each try to do the exchange simultaneously: this race is broken, since exactly one of the processors will perform the exchange first, returning 0, and the second processor will return 1 when it does the exchange. The key to using the exchange primitive to implement synchronization is that the operation is atomic: the exchange is indivisible, and two simultaneous exchanges will be ordered by the hardware. It is impossible for two processors trying to set the synchronization variable in this manner to both think they have simultaneously set the variable.

Implementing a single atomic memory operation introduces some challenges in the design of the processor, since it requires both a memory read and a write in a single, uninterruptible instruction.

An alternative is to have a pair of instructions in which the second instruction returns a value showing whether the pair of instructions was executed as if the pair were atomic. The pair of instructions is effectively atomic if it appears as if all other operations executed by any processor occurred before or after the pair. Thus, when an instruction pair is effectively atomic, no other processor can change the value between the instruction pair.

In MIPS this pair of instructions includes a special load called a *load linked* and a special store called a *store conditional*. These instructions are used in sequence: if the contents of the memory location specified by the load linked are changed before the store conditional to the same address occurs, then the store conditional fails. The store conditional is defined to both store the value of a register in memory *and* to change the value of that register to a 1 if it succeeds and to a 0 if it fails. Since the load linked returns the initial value, and the store conditional returns 1 only if it succeeds, the following sequence implements an atomic exchange on the memory location specified by the contents of \$s1:

```
try: add $t0,$zero,$s4      ;copy exchange value
    ll   $t1,0($s1)        ;load linked
    sc   $t0,0($s1)        ;store conditional
    beq  $t0,$zero,try     ;branch store fails
    add  $s4,$zero,$t1      ;put load value in $s4
```

At the end of this sequence the contents of \$s4 and the memory location specified by \$s1 have been atomically exchanged. Any time a processor intervenes and modifies the value in memory between the ll and sc instructions, the sc returns 0 in \$t0, causing the code sequence to try again.

Elaboration: Although it was presented for multiprocessor synchronization, atomic exchange is also useful for the operating system in dealing with multiple processes in a single processor. To make sure nothing interferes in a single processor, the store conditional also fails if the processor does a context switch between the two instructions (see Chapter 5).

Since the store conditional will fail after either another attempted store to the load linked address or an *y* exception, care must be taken in choosing which instructions are inserted between the two instructions. In particular, only register-register instructions can safely be permitted; otherwise, it is possible to create deadlock situations where the processor can never complete the SC because of repeated page faults. In addition, the number of instructions between the load linked and the store conditional should be small to minimize the probability that either an unrelated event or a competing processor causes the store conditional to fail frequently.

An advantage of the load linked/store conditional mechanism is that it can be used to build other synchronization primitives, such as *atomic compare and swap* or *atomic fetch-and-increment*, which are used in some parallel programming models. These involve more instructions between the LL and the SC.

When do you use primitives like load linked and store conditional?

1. When cooperating threads of a parallel program need to synchronize to get proper behavior for reading and writing shared data
2. When cooperating processes on a uniprocessor need to synchronize for reading and writing shared data

Check Yourself

2.12 Translating and Starting a Program

This section describes the four steps in transforming a C program in a file on disk into a program running on a computer. Figure 2.21 shows the translation hierarchy. Some systems combine these steps to reduce translation time, but these are the logical four phases that programs go through. This section follows this translation hierarchy.

Compiler

The compiler transforms the C program into an *assembly language program*, a symbolic form of what the machine understands. High-level language programs take many fewer lines of code than assembly language, so programmer productivity is much higher.

In 1975, many operating systems and assemblers were written in *assembly language* because memories were small and compilers were inefficient. The 500,000-fold increase in memory capacity per single DRAM chip has reduced program size concerns, and optimizing compilers today can produce assembly language programs nearly as good as an assembly language expert, and sometimes even better for large programs.

assembly language
A symbolic language that can be translated into binary machine language.

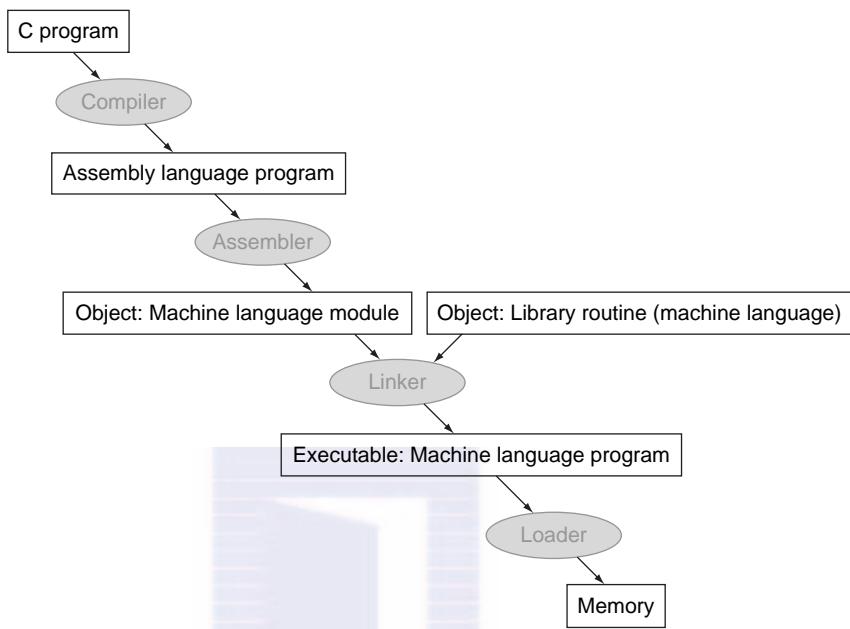


FIGURE 2.21 A translation hierarchy for C. A high-level language program is first compiled into an assembly language program and then assembled into an object module in machine language. The linker combines multiple modules with library routines to resolve all references. The loader then places the machine code into the proper memory locations for execution by the processor. To speed up the translation process, some steps are skipped or combined. Some compilers produce object modules directly, and some systems use linking loaders that perform the last two steps. To identify the type of file, UNIX follows a suffix convention for files: C source files are named `x.c`, assembly files are `x.s`, object files are named `x.o`, statically linked library routines are `x.a`, dynamically linked library routes are `x.so`, and executable files by default are called `a.out`. MS-DOS uses the suffixes `.C`, `.ASM`, `.OBJ`, `.LIB`, `.DLL`, and `.EXE` to the same effect.

Assembler

Since assembly language is an interface to higher-level software, the assembler can also treat common variations of machine language instructions as if they were instructions in their own right. The hardware need not implement these instructions; however, their appearance in assembly language simplifies translation and programming. Such instructions are called **pseudoinstructions**.

As mentioned above, the MIPS hardware makes sure that register \$zero always has the value 0. That is, whenever register \$zero is used, it supplies a 0, and the programmer cannot change the value of register \$zero. Register \$zero is used

pseudoinstruction
A common variation
of assembly language
instructions often treated
as if it were an instruction
in its own right.

to create the assembly language instruction `move` that copies the contents of one register to another. Thus the MIPS assembler accepts this instruction even though it is not found in the MIPS architecture:

```
move $t0,$t1      # register $t0 gets register $t1
```

The assembler converts this assembly language instruction into the machine language equivalent of the following instruction:

```
add $t0,$zero,$t1 # register $t0 gets 0 + register $t1
```

The MIPS assembler also converts `blt` (branch on less than) into the two instructions `slt` and `bne` mentioned in the example on page 128. Other examples include `bgt`, `bge`, and `ble`. It also converts branches to faraway locations into a branch and jump. As mentioned above, the MIPS assembler allows 32-bit constants to be loaded into a register despite the 16-bit limit of the immediate instructions.

In summary, pseudoinstructions give MIPS a richer set of assembly language instructions than those implemented by the hardware. The only cost is reserving one register, `$at`, for use by the assembler. If you are going to write assembly programs, use pseudoinstructions to simplify your task. To understand the MIPS architecture and be sure to get best performance, however, study the real MIPS instructions found in Figures 2.1 and 2.19.

Assemblers will also accept numbers in a variety of bases. In addition to binary and decimal, they usually accept a base that is more succinct than binary yet converts easily to a bit pattern. MIPS assemblers use hexadecimal.

Such features are convenient, but the primary task of an assembler is assembly into machine code. The assembler turns the assembly language program into an *object file*, which is a combination of machine language instructions, data, and information needed to place instructions properly in memory.

To produce the binary version of each instruction in the assembly language program, the assembler must determine the addresses corresponding to all labels. Assemblers keep track of labels used in branches and data transfer instructions in a *symbol table*. As you might expect, the table contains pairs of symbols and addresses.

The object file for UNIX systems typically contains six distinct pieces:

- The *object file header* describes the size and position of the other pieces of the object file.
- The *text segment* contains the machine language code.
- The *static data segment* contains data allocated for the life of the program. (UNIX allows programs to use both *static data*, which is allocated throughout the program, and *dynamic data*, which can grow or shrink as needed by the program. See Figure 2.13.)
- The *relocation information* identifies instructions and data words that depend on absolute addresses when the program is loaded into memory.

symbol table A table that matches names of labels to the addresses of the memory words that instructions occupy.

- The *symbol table* contains the remaining labels that are not defined, such as external references.
- The *debugging information* contains a concise description of how the modules were compiled so that a debugger can associate machine instructions with C source files and make data structures readable.

The next subsection shows how to attach such routines that have already been assembled, such as library routines.

Linker

What we have presented so far suggests that a single change to one line of one procedure requires compiling and assembling the whole program. Complete retranslation is a terrible waste of computing resources. This repetition is particularly wasteful for standard library routines, because programmers would be compiling and assembling routines that by definition almost never change. An alternative is to compile and assemble each procedure independently, so that a change to one line would require compiling and assembling only one procedure. This alternative requires a new systems program, called a **link editor** or **linker**, which takes all the independently assembled machine language programs and “stitches” them together.

There are three steps for the linker:

1. Place code and data modules symbolically in memory.
2. Determine the addresses of data and instruction labels.
3. Patch both the internal and external references.

The linker uses the relocation information and symbol table in each object module to resolve all undefined labels. Such references occur in branch instructions, jump instructions, and data addresses, so the job of this program is much like that of an editor: it finds the old addresses and replaces them with the new addresses. Editing is the origin of the name “link editor,” or linker for short. The reason a linker is useful is that it is much faster to patch code than it is to recompile and reassemble.

If all external references are resolved, the linker next determines the memory locations each module will occupy. Recall that Figure 2.13 on page 120 shows the MIPS convention for allocation of program and data to memory. Since the files were assembled in isolation, the assembler could not know where a module’s instructions and data would be placed relative to other modules. When the linker places a module in memory, all *absolute* references, that is, memory addresses that are not relative to a register, must be *relocated* to reflect its true location.

The linker produces an **executable file** that can be run on a computer. Typically, this file has the same format as an object file, except that it contains no unresolved references. It is possible to have partially linked files, such as library routines, that still have unresolved addresses and hence result in object files.

linker Also called **link editor**. A systems program that combines independently assembled machine language programs and resolves all undefined labels into an executable file.

executable file A functional program in the format of an object file that contains no unresolved references. It can contain symbol tables and debugging information. A “stripped executable” does not contain that information. Relocation information may be included for the loader.

Linking Object Files

Link the two object files below. Show updated addresses of the first few instructions of the completed executable file. We show the instructions in assembly language just to make the example understandable; in reality, the instructions would be numbers.

EXAMPLE

Note that in the object files we have highlighted the addresses and symbols that must be updated in the link process: the instructions that refer to the addresses of procedures A and B and the instructions that refer to the addresses of data words X and Y.

Object file header			
	Name	Procedure A	
	Text size	100 _{hex}	
	Data size	20 _{hex}	
Text segment	Address	Instruction	
	0	lw \$a0, 0(\$gp)	
	4	jal 0	
	
Data segment	0	(X)	
	
Relocation information	Address	Instruction type	Dependency
	0	lw	X
	4	jal	B
Symbol table	Label	Address	
	X	-	
	B	-	
Object file header			
	Name	Procedure B	
	Text size	200 _{hex}	
	Data size	30 _{hex}	
Text segment	Address	Instruction	
	0	sw \$a1, 0(\$gp)	
	4	jal 0	
	
Data segment	0	(Y)	
	
Relocation information	Address	Instruction type	Dependency
	0	sw	Y
	4	jal	A
Symbol table	Label	Address	
	Y	-	
	A	-	

ANSWER

Procedure A needs to find the address for the variable labeled X to put in the load instruction and to find the address of procedure B to place in the `jal` instruction. Procedure B needs the address of the variable labeled Y for the store instruction and the address of procedure A for its `jal` instruction.

From Figure 2.13 on page 120, we know that the text segment starts at address $40\ 0000_{hex}$ and the data segment at $1000\ 0000_{hex}$. The text of procedure A is placed at the first address and its data at the second. The object file header for procedure A says that its text is 100_{hex} bytes and its data is 20_{hex} bytes, so the starting address for procedure B text is $40\ 0100_{hex}$, and its data starts at $1000\ 0020_{hex}$.

Executable file header		
	Text size	300_{hex}
	Data size	50_{hex}
Text segment	Address	Instruction
	$0040\ 0000_{hex}$	<code>lw \$a0, 8000_{hex}(\$gp)</code>
	$0040\ 0004_{hex}$	<code>jal 40 0100_{hex}</code>

	$0040\ 0100_{hex}$	<code>sw \$a1, 8020_{hex}(\$gp)</code>
	$0040\ 0104_{hex}$	<code>jal 40 0000_{hex}</code>

Data segment	Address	
	$1000\ 0000_{hex}$	(X)

	$1000\ 0020_{hex}$	(Y)

Figure 2.13 also shows that the text segment starts at address $40\ 0000_{hex}$ and the data segment at $1000\ 0000_{hex}$. The text of procedure A is placed at the first address and its data at the second. The object file header for procedure A says that its text is 100_{hex} bytes and its data is 20_{hex} bytes, so the starting address for procedure B text is $40\ 0100_{hex}$, and its data starts at $1000\ 0020_{hex}$.

Now the linker updates the address fields of the instructions. It uses the instruction type field to know the format of the address to be edited. We have two types here:

1. The `jal`s are easy because they use pseudodirect addressing. The `jal` at address $40\ 0004_{\text{hex}}$ gets $40\ 0100_{\text{hex}}$ (the address of procedure B) in its address field, and the `jal` at $40\ 0104_{\text{hex}}$ gets $40\ 0000_{\text{hex}}$ (the address of procedure A) in its address field.
2. The load and store addresses are harder because they are relative to a base register. This example uses the global pointer as the base register. Figure 2.13 shows that `$gp` is initialized to $1000\ 8000_{\text{hex}}$. To get the address $1000\ 0000_{\text{hex}}$ (the address of word X), we place 8000_{hex} in the address field of `lw` at address $40\ 0000_{\text{hex}}$. Similarly, we place 8020_{hex} in the address field of `sw` at address $40\ 0100_{\text{hex}}$ to get the address $1000\ 0020_{\text{hex}}$ (the address of word Y).

Elaboration: Recall that MIPS instructions are word aligned, so `jal` drops the right two bits to increase the instruction's address range. Thus, it uses 26 bits to create a 28-bit byte address. Hence, the actual address in the lower 26 bits of the `jal` instruction in this example is $10\ 0040_{\text{hex}}$, rather than $40\ 0100_{\text{hex}}$.

Loader

Now that the executable file is on disk, the operating system reads it to memory and starts it. The **loader** follows these steps in UNIX systems:

1. Reads the executable file header to determine size of the text and data segments.
2. Creates an address space large enough for the text and data.
3. Copies the instructions and data from the executable file into memory.
4. Copies the parameters (if any) to the main program onto the stack.
5. Initializes the machine registers and sets the stack pointer to the first free location.
6. Jumps to a start-up routine that copies the parameters into the argument registers and calls the main routine of the program. When the main routine returns, the start-up routine terminates the program with an `exit` system call.

loader A systems program that places an object program in main memory so that it is ready to execute.

Sections B.3 and B.4 in Appendix B describe linkers and loaders in more detail.

Dynamically Linked Libraries

The first part of this section describes the traditional approach to linking libraries before the program is run. Although this static approach is the fastest way to call library routines, it has a few disadvantages:

- The library routines become part of the executable code. If a new version of the library is released that fixes bugs or supports new hardware devices, the statically linked program keeps using the old version.
- It loads all routines in the library that are called anywhere in the executable, even if those calls are not executed. The library can be large relative to the program; for example, the standard C library is 2.5 MB.

dynamically linked libraries (DLLs) Library routines that are linked to a program during execution.

These disadvantages lead to **dynamically linked libraries (DLLs)**, where the library routines are not linked and loaded until the program is run. Both the program and library routines keep extra information on the location of nonlocal procedures and their names. In the initial version of DLLs, the loader ran a dynamic linker, using the extra information in the file to find the appropriate libraries and to update all external references.

The downside of the initial version of DLLs was that it still linked all routines of the library that might be called, versus only those that are called during the running of the program. This observation led to the lazy procedure linkage version of DLLs, where each routine is linked only *after* it is called.

Like many innovations in our field, this trick relies on a level of indirection. Figure 2.22 shows the technique. It starts with the nonlocal routines calling a set of dummy routines at the end of the program, with one entry per nonlocal routine. These dummy entries each contain an indirect jump.

The first time the library routine is called, the program calls the dummy entry and follows the indirect jump. It points to code that puts a number in a register to identify the desired library routine and then jumps to the dynamic linker/loader. The linker/loader finds the desired routine, remaps it, and changes the address in the indirect jump location to point to that routine. It then jumps to it. When the routine completes, it returns to the original calling site. Thereafter, the call to the library routine jumps indirectly to the routine without the extra hops.

In summary, DLLs require extra space for the information needed for dynamic linking, but do not require that whole libraries be copied or linked. They pay a good deal of overhead the first time a routine is called, but only a single indirect jump thereafter. Note that the return from the library pays no extra overhead. Microsoft's Windows relies extensively on dynamically linked libraries, and it is also the default when executing programs on UNIX systems today.

Starting a Java Program

The discussion above captures the traditional model of executing a program, where the emphasis is on fast execution time for a program targeted to a specific instruction set architecture, or even a specific implementation of that architecture. Indeed, it is possible to execute Java programs just like C. Java was invented with a different set of goals, however. One was to run safely on any computer, even if it might slow execution time.

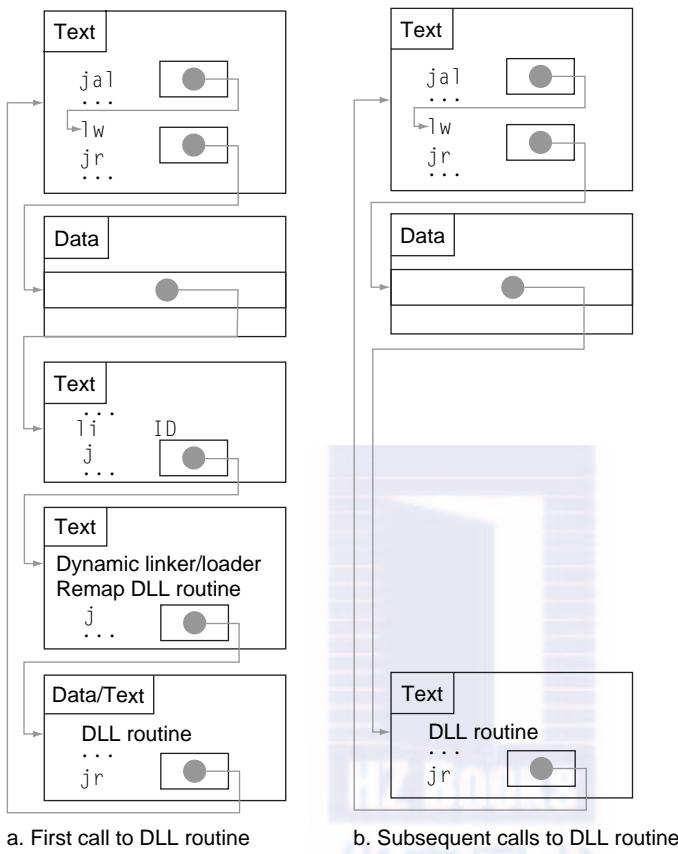


FIGURE 2.22 Dynamically linked library via lazy procedure linkage. (a) Steps for the first time a call is made to the DLL routine. (b) The steps to find the routine, remap it, and link it are skipped on subsequent calls. As we will see in Chapter 5, the operating system may avoid copying the desired routine by remapping it using virtual memory management.

Figure 2.23 shows the typical translation and execution steps for Java. Rather than compile to the assembly language of a target computer, Java is compiled first to instructions that are easy to interpret: the **Java bytecode** instruction set (see [Section 2.15](#) on the CD). This instruction set is designed to be close to the Java language so that this compilation step is trivial. Virtually no optimizations are performed. Like the C compiler, the Java compiler checks the types of data and produces the proper operation for each type. Java programs are distributed in the binary version of these bytecodes.

A software interpreter, called a **Java Virtual Machine (JVM)**, can execute Java bytecodes. An interpreter is a program that simulates an instruction set architecture. For example, the MIPS simulator used with this book is an interpreter. There is no need for a separate assembly step since either the translation is so simple that the compiler fills in the addresses or JVM finds them at runtime.

Java bytecode
Instruction from an instruction set designed to interpret Java programs.

Java Virtual Machine (JVM) The program that interprets Java bytecodes.

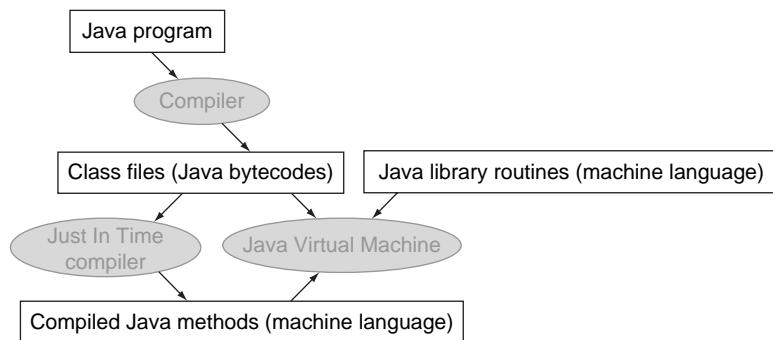


FIGURE 2.23 A translation hierarchy for Java. A Java program is first compiled into a binary version of Java bytecodes, with all addresses defined by the compiler. The Java program is now ready to run on the interpreter, called the Java Virtual Machine (JVM). The JVM links to desired methods in the Java library while the program is running. To achieve greater performance, the JVM can invoke the JIT compiler, which selectively compiles methods into the native machine language of the machine on which it is running.

The upside of interpretation is portability. The availability of software Java virtual machines meant that most people could write and run Java programs shortly after Java was announced. Today, Java virtual machines are found in hundreds of millions of devices, in everything from cell phones to Internet browsers.

The downside of interpretation is lower performance. The incredible advances in performance of the 1980s and 1990s made interpretation viable for many important applications, but the factor of 10 slowdown when compared to traditionally compiled C programs made Java unattractive for some applications.

To preserve portability and improve execution speed, the next phase of Java development was compilers that translated *while* the program was running. Such **Just In Time compilers (JIT)** typically profile the running program to find where the “hot” methods are and then compile them into the native instruction set on which the virtual machine is running. The compiled portion is saved for the next time the program is run, so that it can run faster each time it is run. This balance of interpretation and compilation evolves over time, so that frequently run Java programs suffer little of the overhead of interpretation.

As computers get faster so that compilers can do more, and as researchers invent better ways to compile Java on the fly, the performance gap between Java and C or C++ is closing. ☐ Section 2.15 on the CD goes into much greater depth on the implementation of Java, Java bytecodes, JVM, and JIT compilers.

Just In Time compiler (JIT) The name commonly given to a compiler that operates at runtime, translating the interpreted code segments into the native code of the computer.

Check Yourself

Which of the advantages of an interpreter over a translator do you think was most important for the designers of Java?

1. Ease of writing an interpreter
2. Better error messages
3. Smaller object code
4. Machine independence

2.13

A C Sort Example to Put It All Together

One danger of showing assembly language code in snippets is that you will have no idea what a full assembly language program looks like. In this section, we derive the MIPS code from two procedures written in C: one to swap array elements and one to sort them.

```
void swap(int v[], int k)
{
    int temp;
    temp = v[k];
    v[k] = v[k+1];
    v[k+1] = temp;
}
```

FIGURE 2.24 A C procedure that swaps two locations in memory. This subsection uses this procedure in a sorting example.

The Procedure `swap`

Let's start with the code for the procedure `swap` in Figure 2.24. This procedure simply swaps two locations in memory. When translating from C to assembly language by hand, we follow these general steps:

1. Allocate registers to program variables.
2. Produce code for the body of the procedure.
3. Preserve registers across the procedure invocation.

This section describes the `swap` procedure in these three pieces, concluding by putting all the pieces together.

Register Allocation for `swap`

As mentioned on pages 112–113, the MIPS convention on parameter passing is to use registers \$a0, \$a1, \$a2, and \$a3. Since `swap` has just two parameters, `v` and `k`, they will be found in registers \$a0 and \$a1. The only other variable is `temp`, which we associate with register \$t0 since `swap` is a leaf procedure (see page 116).

This register allocation corresponds to the variable declarations in the first part of the `swap` procedure in Figure 2.24.

Code for the Body of the Procedure `swap`

The remaining lines of C code in `swap` are

```
temp = v[k];
v[k] = v[k+1];
v[k+1] = temp;
```

Recall that the memory address for MIPS refers to the *byte* address, and so words are really 4 bytes apart. Hence we need to multiply the index k by 4 before adding it to the address. *Forgetting that sequential word addresses differ by 4 instead of by 1 is a common mistake in assembly language programming.* Hence the first step is to get the address of $v[k]$ by multiplying k by 4 via a shift left by 2:

```
sll    $t1, $a1,2      # reg $t1 = k * 4
add    $t1, $a0,$t1    # reg $t1 = v + (k * 4)
                      # reg $t1 has the address of v[k]
```

Now we load $v[k]$ using $\$t1$, and then $v[k+1]$ by adding 4 to $\$t1$:

```
lw     $t0, 0($t1)    # reg $t0 (temp) = v[k]
lw     $t2, 4($t1)    # reg $t2 = v[k + 1]
                      # refers to next element of v
```

Next we store $\$t0$ and $\$t2$ to the swapped addresses:

```
sw     $t2, 0($t1)    # v[k] = reg $t2
sw     $t0, 4($t1)    # v[k+1] = reg $t0 (temp)
```

Now we have allocated registers and written the code to perform the operations of the procedure. What is missing is the code for preserving the saved registers used within `swap`. Since we are not using saved registers in this leaf procedure, there is nothing to preserve.

The Full `swap` Procedure

We are now ready for the whole routine, which includes the procedure label and the return jump. To make it easier to follow, we identify in Figure 2.25 each block of code with its purpose in the procedure.

The Procedure `sort`

To ensure that you appreciate the rigor of programming in assembly language, we'll try a second, longer example. In this case, we'll build a routine that calls the `swap` procedure. This program sorts an array of integers, using bubble or exchange sort, which is one of the simplest if not the fastest sorts. Figure 2.26 shows the C

Procedure body	
swap: sll	\$t1, \$a1, 2
add	\$t1, \$a0, \$t1
lw	\$t0, 0(\$t1)
lw	\$t2, 4(\$t1)
sw	\$t2, 0(\$t1)
sw	\$t0, 4(\$t1)
	# reg \$t1 = k * 4 # reg \$t1 = v + (k * 4) # reg \$t1 has the address of v[k] # reg \$t0 (temp) = v[k] # reg \$t2 = v[k + 1] # refers to next element of v # v[k] = reg \$t2 # v[k+1] = reg \$t0 (temp)
Procedure return	
jr	\$ra
	# return to calling routine

FIGURE 2.25 MIPS assembly code of the procedure swap in Figure 2.24.

version of the program. Once again, we present this procedure in several steps, concluding with the full procedure.

```
void sort (int v[], int n)
{
    int i, j;
    for (i = 0; i < n; i += 1) {
        for (j = i - 1; j >= 0 && v[j] > v[j + 1]; j -= 1) {
            swap(v, j);
        }
    }
}
```

FIGURE 2.26 A C procedure that performs a sort on the array v.

Register Allocation for sort

The two parameters of the procedure sort, v and n, are in the parameter registers \$a0 and \$a1, and we assign register \$s0 to i and register \$s1 to j.

Code for the Body of the Procedure sort

The procedure body consists of two nested *for* loops and a call to swap that includes parameters. Let's unwrap the code from the outside to the middle.

The first translation step is the first *for* loop:

```
for (i = 0; i < n; i += 1) {
```

Recall that the C *for* statement has three parts: initialization, loop test, and iteration increment. It takes just one instruction to initialize i to 0, the first part of the *for* statement:

```
move    $s0, $zero      # i = 0
```

(Remember that `move` is a pseudoinstruction provided by the assembler for the convenience of the assembly language programmer; see page 141.) It also takes just one instruction to increment `i`, the last part of the `for` statement:

```
addi    $s0, $s0, 1      # i += 1
```

The loop should be exited if $i < n$ is *not* true or, said another way, should be exited if $i \geq n$. The set on less than instruction sets register `$t0` to 1 if $\$s0 < \$a1$ and to 0 otherwise. Since we want to test if $\$s0 \geq \$a1$, we branch if register `$t0` is 0. This test takes two instructions:

```
forltst:slt $t0, $s0, $a1 # reg $t0 = 0 if $s0 \geq $a1 (i\geq n)
           beq $t0, $zero,exit1 # go to exit1 if $s0 \geq $a1 (i\geq n)
```

The bottom of the loop just jumps back to the loop test:

```
j   forltst          # jump to test of outer loop
exit1:
```

The skeleton code of the first `for` loop is then

```
move  $s0, $zero      # i = 0
forltst:slt $t0, $s0, $a1 # reg $t0 = 0 if $s0 \geq $a1 (i\geq n)
           beq $t0, $zero,exit1 # go to exit1 if $s0 \geq $a1 (i\geq n)
           ...
           (body of first for loop)
           ...
addi  $s0, $s0, 1      # i += 1
j     forltst          # jump to test of outer loop
exit1:
```

Voila! (The exercises explore writing faster code for similar loops.)

The second `for` loop looks like this in C:

```
for (j = i - 1; j >= 0 && v[j] > v[j + 1]; j -= 1) {
```

The initialization portion of this loop is again one instruction:

```
addi  $s1, $s0, -1 # j = i - 1
```

The decrement of `j` at the end of the loop is also one instruction:

```
addi  $s1, $s1, -1 # j -= 1
```

The loop test has two parts. We exit the loop if either condition fails, so the first test must exit the loop if it fails ($j < 0$):

```
for2tst: slti $t0, $s1, 0 # reg $t0 = 1 if $s1 < 0 (j < 0)
           bne $t0, $zero, exit2 # go to exit2 if $s1 < 0 (j < 0)
```

This branch will skip over the second condition test. If it doesn't skip, $j \geq 0$.

The second test exits if $v[j] > v[j + 1]$ is *not* true, or exits if $v[j] \leq v[j + 1]$. First we create the address by multiplying j by 4 (since we need a byte address) and add it to the base address of v :

```
sll      $t1, $s1, 2    # reg $t1 = j * 4
add      $t2, $a0, $t1 # reg $t2 = v + (j * 4)
```

Now we load $v[j]$:

```
lw      $t3, 0($t2)  # reg $t3 = v[j]
```

Since we know that the second element is just the following word, we add 4 to the address in register $$t2$ to get $v[j + 1]$:

```
lw      $t4, 4($t2)  # reg $t4 = v[j + 1]
```

The test of $v[j] \leq v[j + 1]$ is the same as $v[j + 1] \geq v[j]$, so the two instructions of the exit test are

```
slt      $t0, $t4, $t3    # reg $t0 = 0 if $t4 \geq $t3
beq      $t0, $zero, exit2 # go to exit2 if $t4 \geq $t3
```

The bottom of the loop jumps back to the inner loop test:

```
j      for2tst  # jump to test of inner loop
```

Combining the pieces, the skeleton of the second *for* loop looks like this:

```
addi $s1, $s0, -1    # j = i - 1
for2tst: slti $t0, $s1, 0    # reg $t0 = 1 if $s1 < 0 (j < 0)
               bne $t0, $zero, exit2 # go to exit2 if $s1 < 0 (j < 0)
               sll $t1, $s1, 2    # reg $t1 = j * 4
               add $t2, $a0, $t1  # reg $t2 = v + (j * 4)
               lw   $t3, 0($t2)  # reg $t3 = v[j]
               lw   $t4, 4($t2)  # reg $t4 = v[j + 1]
               slt $t0, $t4, $t3    # reg $t0 = 0 if $t4 \geq $t3
               beq $t0, $zero, exit2 # go to exit2 if $t4 \geq $t3
               ...
               (body of second for loop)
               ...
               addi $s1, $s1, -1    # j -= 1
               j     for2tst        # jump to test of inner loop
exit2:
```

The Procedure Call in sort

The next step is the body of the second *for* loop:

```
swap(v, j);
```

Calling `swap` is easy enough:

```
jal    swap
```

Passing Parameters in sort

The problem comes when we want to pass parameters because the `sort` procedure needs the values in registers `$a0` and `$a1`, yet the `swap` procedure needs to have its parameters placed in those same registers. One solution is to copy the parameters for `sort` into other registers earlier in the procedure, making registers `$a0` and `$a1` available for the call of `swap`. (This copy is faster than saving and restoring on the stack.) We first copy `$a0` and `$a1` into `$s2` and `$s3` during the procedure:

```
move $s2, $a0      # copy parameter $a0 into $s2
move $s3, $a1      # copy parameter $a1 into $s3
```

Then we pass the parameters to `swap` with these two instructions:

```
move $a0, $s2      # first swap parameter is v
move $a1, $s1      # second swap parameter is j
```

Preserving Registers in sort

The only remaining code is the saving and restoring of registers. Clearly, we must save the return address in register `$ra`, since `sort` is a procedure and is called itself. The `sort` procedure also uses the saved registers `$s0`, `$s1`, `$s2`, and `$s3`, so they must be saved. The prologue of the `sort` procedure is then

```
addi $sp,$sp,-20    # make room on stack for 5 registers
sw   $ra,16($sp)    # save $ra on stack
sw   $s3,12($sp)    # save $s3 on stack
sw   $s2, 8($sp)    # save $s2 on stack
sw   $s1, 4($sp)    # save $s1 on stack
sw   $s0, 0($sp)    # save $s0 on stack
```

The tail of the procedure simply reverses all these instructions, then adds a `jr` to return.

The Full Procedure sort

Now we put all the pieces together in Figure 2.27, being careful to replace references to registers `$a0` and `$a1` in the *for* loops with references to registers `$s2` and `$s3`. Once again, to make the code easier to follow, we identify each block of code with its purpose in the procedure. In this example, nine lines of the `sort` procedure in C became 35 lines in the MIPS assembly language.

Elaboration: One optimization that works with this example is *procedure inlining*. Instead of passing arguments in parameters and invoking the code with a `jal` instruction, the compiler would copy the code from the body of the `swap` procedure where the call to `swap` appears in the code. Inlining would avoid four instructions in this example. The downside of the inlining optimization is that the compiled code would be bigger if the inlined procedure is called from several locations. Such a code expansion might turn into *lower* performance if it increased the cache miss rate; see Chapter 5.

Saving registers		
	sort:	<pre> addi \$sp,\$sp, -20 # make room on stack for 5 registers sw \$ra, 16(\$sp) # save \$ra on stack sw \$s3,12(\$sp) # save \$s3 on stack sw \$s2, 8(\$sp) # save \$s2 on stack sw \$s1, 4(\$sp) # save \$s1 on stack sw \$s0, 0(\$sp) # save \$s0 on stack </pre>
Procedure body		
Move parameters		<pre> move \$s2, \$a0 # copy parameter \$a0 into \$s2 (save \$a0) move \$s3, \$a1 # copy parameter \$a1 into \$s3 (save \$a1) </pre>
Outer loop	for1tst:	<pre> move \$s0, \$zero# i = 0 slt\$t0, \$s0, \$s3 # reg \$t0 = 0 if \$s0 <= \$s3 (i < n) beq \$t0, \$zero, exit1# go to exit1 if \$s0 <= \$s3 (i < n) </pre>
Inner loop	for2tst:	<pre> addi \$s1, \$s0, -1# j = i - 1 slti\$t0, \$s1, 0 # reg \$t0 = 1 if \$s1 < 0 (j < 0) bne \$t0, \$zero, exit2# go to exit2 if \$s1 < 0 (j < 0) sll \$t1, \$s1, 2# reg \$t1 = j * 4 add \$t2, \$s2, \$t1# reg \$t2 = v + (j * 4) lw \$t3, 0(\$t2)# reg \$t3 = v[j] lw \$t4, 4(\$t2)# reg \$t4 = v[j + 1] slt \$t0, \$t4, \$t3 # reg \$t0 = 0 if \$t4 <= \$t3 beq \$t0, \$zero, exit2# go to exit2 if \$t4 <= \$t3 </pre>
Pass parameters and call		<pre> move \$a0, \$s2 # 1st parameter of swap is v (old \$a0) move \$a1, \$s1 # 2nd parameter of swap is j jal swap # swap code shown in Figure 2.25 </pre>
Inner loop		<pre> addi \$s1, \$s1, -1# j -= 1 j for2tst # jump to test of inner loop </pre>
Outer loop	exit2:	<pre> addi \$s0, \$s0, 1 # i += 1 j for1tst # jump to test of outer loop </pre>
Restoring registers		
	exit1:	<pre> lw \$s0, 0(\$sp) # restore \$s0 from stack lw \$s1, 4(\$sp) # restore \$s1 from stack lw \$s2, 8(\$sp) # restore \$s2 from stack lw \$s3,12(\$sp) # restore \$s3 from stack lw \$ra,16(\$sp) # restore \$ra from stack addi \$sp,\$sp, 20 # restore stack pointer </pre>
Procedure return		
	jr	\$ra # return to calling routine

FIGURE 2.27 MIPS assembly version of procedure sort in Figure 2.26.

Understanding Program Performance

Figure 2.28 shows the impact of compiler optimization on sort program performance, compile time, clock cycles, instruction count, and CPI. Note that unoptimized code has the best CPI, and O1 optimization has the lowest instruction count, but O3 is the fastest, reminding us that time is the only accurate measure of program performance.

Figure 2.29 compares the impact of programming languages, compilation versus interpretation, and algorithms on performance of sorts. The fourth column shows that the unoptimized C program is 8.3 times faster than the interpreted Java code for Bubble Sort. Using the JIT compiler makes Java 2.1 times *faster* than the unoptimized C and within a factor of 1.13 of the highest optimized C code. (Section 2.15 on the CD gives more details on interpretation versus compilation of Java and the Java and MIPS code for Bubble Sort.) The ratios aren't as close for Quicksort in Column 5, presumably because it is harder to amortize the cost of runtime compilation over the shorter execution time. The last column demonstrates the impact of a better algorithm, offering three orders of magnitude a performance increases by when sorting 100,000 items. Even comparing interpreted Java in Column 5 to the C compiler at highest optimization in Column 4, Quicksort beats Bubble Sort by a factor of 50 (0.05×2468 , or 123 times faster than the unoptimized C code versus 2.41 times faster).

Elaboration: The MIPS compiler always save room on the stack for the arguments in case they need to be stored, so in reality they always decrement \$sp by 16 to make room for all four argument registers (16 bytes). One reason is that C provides a vararg option that allows a pointer to pick, say, the third argument to a procedure. When the compiler encounters the rare vararg, it copies the four argument registers onto the stack into the four reserved locations.

gcc optimization	Relative performance	Clock cycles (millions)	Instruction count (millions)	CPI
None	1.00	158,615	114,938	1.38
O1 (medium)	2.37	66,990	37,470	1.79
O2 (full)	2.38	66,521	39,993	1.66
O3 (procedure integration)	2.41	65,747	44,993	1.46

FIGURE 2.28 Comparing performance, instruction count, and CPI using compiler optimization for Bubble Sort. The programs sorted 100,000 words with the array initialized to random values. These programs were run on a Pentium 4 with a clock rate of 3.06 GHz and a 533 MHz system bus with 2 GB of PC2100 DDR SDRAM. It used Linux version 2.4.20.

Language	Execution method	Optimization	Bubble Sort relative performance	Quicksort relative performance	Speedup Quicksort vs. Bubble Sort
C	Compiler	None	1.00	1.00	2468
	Compiler	O1	2.37	1.50	1562
	Compiler	O2	2.38	1.50	1555
	Compiler	O3	2.41	1.91	1955
Java	Interpreter	-	0.12	0.05	1050
	JIT compiler	-	2.13	0.29	338

FIGURE 2.29 Performance of two sort algorithms in C and Java using interpretation and optimizing compilers relative to unoptimized C version. The last column shows the advantage in performance of Quicksort over Bubble Sort for each language and execution option. These programs were run on the same system as Figure 2.28. The JVM is Sun version 1.3.1, and the JIT is Sun Hotspot version 1.3.1.

2.14

Arrays versus Pointers

A challenge for any new C programmer is understanding pointers. Comparing assembly code that uses arrays and array indices to the assembly code that uses pointers offers insights about pointers. This section shows C and MIPS assembly versions of two procedures to clear a sequence of words in memory: one using array indices and one using pointers. Figure 2.30 shows the two C procedures.

The purpose of this section is to show how pointers map into MIPS instructions, and not to endorse a dated programming style. We'll see the impact of modern compiler optimization on these two procedures at the end of the section.

Array Version of Clear

Let's start with the array version, `clear1`, focusing on the body of the loop and ignoring the procedure linkage code. We assume that the two parameters `array` and `size` are found in the registers `$a0` and `$a1`, and that `i` is allocated to register `$t0`.

The initialization of `i`, the first part of the *for* loop, is straightforward:

```
move      $t0,$zero      # i = 0 (register $t0 = 0)
```

To set `array[i]` to 0 we must first get its address. Start by multiplying `i` by 4 to get the byte address:

```
loop1: sll      $t1,$t0,2      # $t1 = i * 4
```

Since the starting address of the array is in a register, we must add it to the index to get the address of `array[i]` using an add instruction:

```
add      $t2,$a0,$t1      # $t2 = address of array[i]
```

Finally, we can store 0 in that address:

```

clear1(int array[], int size)
{
    int i;
    for (i = 0; i < size; i += 1)
        array[i] = 0;
}

clear2(int *array, int size)
{
    int *p;
    for (p = &array[0]; p <
&array[size]; p = p + 1)
        *p = 0;
}

```

FIGURE 2.30 Two C procedures for setting an array to all zeros. Clear1 uses indices, while clear2 uses pointers. The second procedure needs some explanation for those unfamiliar with C. The address of a variable is indicated by `&`, and the object pointed to by a pointer is indicated by `*`. The declarations declare that `array` and `p` are pointers to integers. The first part of the `for` loop in clear2 assigns the address of the first element of `array` to the pointer `p`. The second part of the `for` loop tests to see if the pointer is pointing beyond the last element of `array`. Incrementing a pointer by one, in the last part of the `for` loop, means moving the pointer to the next sequential object of its declared size. Since `p` is a pointer to integers, the compiler will generate MIPS instructions to increment `p` by four, the number of bytes in a MIPS integer. The assignment in the loop places 0 in the object pointed to by `p`.

```
sw      $zero, 0($t2)  # array[i] = 0
```

This instruction is the end of the body of the loop, so the next step is to increment `i`:

```
addi   $t0,$t0,1      # i = i + 1
```

The loop test checks if `i` is less than `size`:

```
slt    $t3,$t0,$a1      # $t3 = (i < size)
bne    $t3,$zero,loop1  # if (i < size) go to loop1
```

We have now seen all the pieces of the procedure. Here is the MIPS code for clearing an array using indices:

```

move   $t0,$zero      # i = 0
loop1: sll   $t1,$t0,2      # $t1 = i * 4
       add   $t2,$a0,$t1      # $t2 = address of array[i]
       sw    $zero, 0($t2)  # array[i] = 0
       addi $t0,$t0,1      # i = i + 1
       slt   $t3,$t0,$a1      # $t3 = (i < size)
       bne   $t3,$zero,loop1 # if (i < size) go to loop1

```

(This code works as long as `size` is greater than 0; ANSI C requires a test of `size` before the loop, but we'll skip that legality here.)

Pointer Version of Clear

The second procedure that uses pointers allocates the two parameters `array` and `size` to the registers `$a0` and `$a1` and allocates `p` to register `$t0`. The code for the second procedure starts with assigning the pointer `p` to the address of the first element of the array:

```
move $t0,$a0          # p = address of array[0]
```

The next code is the body of the *for* loop, which simply stores 0 into `p`:

```
loop2: sw $zero,0($t0)    # Memory[p] = 0
```

This instruction implements the body of the loop, so the next code is the iteration increment, which changes `p` to point to the next word:

```
addi $t0,$t0,4          # p = p + 4
```

Incrementing a pointer by 1 means moving the pointer to the next sequential object in C. Since `p` is a pointer to integers, each of which uses 4 bytes, the compiler increments `p` by 4.

The loop test is next. The first step is calculating the address of the last element of `array`. Start with multiplying `size` by 4 to get its byte address:

```
sll $t1,$a1,2          # $t1 = size * 4
```

and then we add the product to the starting address of the array to get the address of the first word *after* the array:

```
add $t2,$a0,$t1          # $t2 = address of array[size]
```

The loop test is simply to see if `p` is less than the last element of `array`:

```
slt $t3,$t0,$t2          # $t3 = (p < &array[size])
bne $t3,$zero,loop2      # if (p < &array[size]) go to loop2
```

With all the pieces completed, we can show a pointer version of the code to zero an array:

```
move $t0,$a0          # p = address of array[0]
loop2: sw $zero,0($t0)    # Memory[p] = 0
addi $t0,$t0,4          # p = p + 4
sll $t1,$a1,2          # $t1 = size * 4
add $t2,$a0,$t1          # $t2 = address of array[size]
slt $t3,$t0,$t2          # $t3 = (p < &array[size])
bne $t3,$zero,loop2      # if (p < &array[size]) go to loop2
```

As in the first example, this code assumes `size` is greater than 0.

Note that this program calculates the address of the end of the array in every iteration of the loop, even though it does not change. A faster version of the code moves this calculation outside the loop:

```

move  $t0,$a0          # p = address of array[0]
sll   $t1,$a1,2        # $t1 = size * 4
add   $t2,$a0,$t1       # $t2 = address of array[size]
loop2:sw$zero,0($t0)    # Memory[p] = 0
addi  $t0,$t0,4         # p = p + 4
slt   $t3,$t0,$t2       # $t3 = (p < &array[size])
bne   $t3,$zero,loop2  # if (p < &array[size]) go to loop2

```

Comparing the Two Versions of Clear

Comparing the two code sequences side by side illustrates the difference between array indices and pointers (the changes introduced by the pointer version are highlighted):

<pre> move \$t0,\$zero # i = 0 loop1:sll \$t1,\$t0,2 # \$t1 = i * 4 add \$t2,\$a0,\$t1 # \$t2 = &array[i] sw \$zero, 0(\$t2) # array[i] = 0 addi \$t0,\$t0,1 # i = i + 1 slt \$t3,\$t0,\$a1 # \$t3 = (i < size) bne \$t3,\$zero,loop1# if () go to loop1 </pre>	<pre> move \$t0,\$a0 # p = & array[0] sll \$t1,\$a1,2 # \$t1 = size * 4 add \$t2,\$a0,\$t1 # \$t2 = &array[size] loop2:sw \$zero,0(\$t0) # Memory[p] = 0 addi \$t0,\$t0,4 # p = p + 4 slt \$t3,\$t0,\$t2 # \$t3=(p < &array[size]) bne \$t3,\$zero,loop2# if () go to loop2 </pre>
---	---

The version on the left must have the “multiply” and add inside the loop because *i* is incremented and each address must be recalculated from the new index. The memory pointer version on the right increments the pointer *p* directly. The pointer version moves them outside the loop, thereby reducing the instructions executed per iteration from 6 to 4. This manual optimization corresponds to the compiler optimization of strength reduction (shift instead of multiply) and induction variable elimination (eliminating array address calculations within loops). ☺ Section 2.15 on the CD describes these two and many other optimizations.

Elaboration: As mentioned earlier, a C compiler would add a test to be sure that *size* is greater than 0. One way would be to add a jump just before the first instruction of the loop to the *slt* instruction.

People used to be taught to use pointers in C to get greater efficiency than that available with arrays: “Use pointers, even if you can’t understand the code.” Modern optimizing compilers can produce code for the array version that is just as good. Most programmers today prefer that the compiler do the heavy lifting.

Understanding Program Performance



Advanced Material: Compiling C and Interpreting Java

This section gives a brief overview of how the C compiler works and how Java is executed. Because the compiler will significantly affect the performance of a computer, understanding compiler technology today is critical to understanding performance. Keep in mind that the subject of compiler construction is usually taught in a one- or two-semester course, so our introduction will necessarily only touch on the basics.

The second part of this section is for readers interested in seeing how an object oriented language like Java executes on a MIPS architecture. It shows the Java bytecodes used for interpretation and the MIPS code for the Java version of some of the C segments in prior sections, including Bubble Sort. It covers both the Java Virtual Machine and JIT compilers.

The rest of this section is on the CD.

object oriented language A programming language that is oriented around objects rather than actions, or data versus logic.

2.16 Real Stuff: ARM Instructions

ARM is the most popular instruction set architecture for embedded devices, with more than three billion devices per year using ARM. Standing originally for the Acorn RISC Machine, later changed to Advanced RISC Machine, ARM came out the same year as MIPS and followed similar philosophies. Figure 2.31 lists the similarities. The principle difference is that MIPS has more registers and ARM has more addressing modes.

There is a similar core of instruction sets for arithmetic-logical and data transfer instructions for MIPS and ARM, as Figure 2.32 shows.

Addressing Modes

Figure 2.33 shows the data addressing modes supported by ARM. Unlike MIPS, ARM does not reserve a register to contain 0. Although MIPS has just three simple data addressing modes (see Figure 2.18), ARM has nine, including fairly complex calculations. For example, ARM has an addressing mode that can shift one register

	ARM	MIPS
Date announced	1985	1985
Instruction size (bits)	32	32
Address space (size, model)	32 bits, f at	32 bits, f at
Data alignment	Aligned	Aligned
Data addressing modes	9	3
Integer register s (number, model, size)	15 GPR × 32 bits	31 GPR × 32 bits
I/O	Memory mapped	Memory mapped

FIGURE 2.31 Similarities in ARM and MIPS instruction sets.

	Instruction name	ARM	MIPS
Register-register	Add	add	addu, addiu
	Add (trap if overf ow)	adds; swivs	add
	Subtract	sub	subu
	Subtract (trap if overf ow)	subs; swivs	sub
	Multiply	mul	mult, multu
	Divide	—	div, divu
	And	and	and
	Or	orr	or
	Xor	eor	xor
	Load high part register	—	lui
	Shift left logical	lsl ¹	sllv, sll
	Shift right logical	lsr ¹	srlv, srl
	Shift right arithmetic	asr ¹	sra, sra
	Compare	cmp, cmn, tst, teq	slt/i, slt/iu
Data transfer	Load byte signed	ldrsb	lb
	Load byte unsigned	ldrb	ibu
	Load halfword signed	ldrsh	lh
	Load halfword unsigned	ldrh	ihu
	Load word	ldr	lw
	Store byte	strb	sb
	Store halfword	strh	sh
	Store word	str	sw
	Read, write special register s	mrs, msr	move
	Atomic Exchange	swp, swpb	ll;sc

FIGURE 2.32 ARM register-register and data transfer instructions equivalent to MIPS core. Dashes mean the operation is not available in that architecture or not synthesized in a few instructions. If there are several choices of instructions equivalent to the MIPS core, they are separated by commas. ARM includes shifts as part of every data operation instruction, so the shifts with superscript 1 are just a variation of a move instruction, such as lsr¹. Note that ARM has no divide instruction.

by any amount, add it to the other registers to form the address, and then update one register with this new address.

Addressing mode	ARM v.4	MIPS
Register operand	X	X
Immediate operand	X	X
Register + offset (displacement or based)	X	X
Register + register (indexed)	X	—
Register + scaled register (scaled)	X	—
Register + offset and update register	X	—
Register + register and update register	X	—
Autoincrement, autodecrement	X	—
PC-relative data	X	—

FIGURE 2.33 Summary of data addressing modes. ARM has separate register indirect and register + offset addressing modes, rather than just putting 0 in the offset of the latter mode. To get greater addressing range, ARM shifts the offset left 1 or 2 bits if the data size is halfword or word.

Compare and Conditional Branch

MIPS uses the contents of registers to evaluate conditional branches. ARM uses the traditional four condition code bits stored in the program status word: *negative*, *zero*, *carry*, and *overflow*. They can be set on any arithmetic or logical instruction; unlike earlier architectures, this setting is optional on each instruction. An explicit option leads to fewer problems in a pipelined implementation. ARM uses conditional branches to test condition codes to determine all possible unsigned and signed relations.

CMP subtracts one operand from the other and the difference sets the condition codes. Compare negative (CMN) adds one operand to the other, and the sum sets the condition codes. TST performs logical AND on the two operands to set all condition codes but overflow, while TEQ uses exclusive OR to set the first three condition codes.

One unusual feature of ARM is that every instruction has the option of executing conditionally, depending on the condition codes. Every instruction starts with a 4-bit field that determines whether it will act as a no operation instruction (nop) or as a real instruction, depending on the condition codes. Hence, conditional branches are properly considered as conditionally executing the unconditional branch instruction. Conditional execution allows avoiding a branch to jump over a single instruction. It takes less code space and time to simply conditionally execute one instruction.

Figure 2.34 shows the instruction formats for ARM and MIPS. The principal differences are the 4-bit conditional execution field in every instruction and the smaller register field, because ARM has half the number of registers.

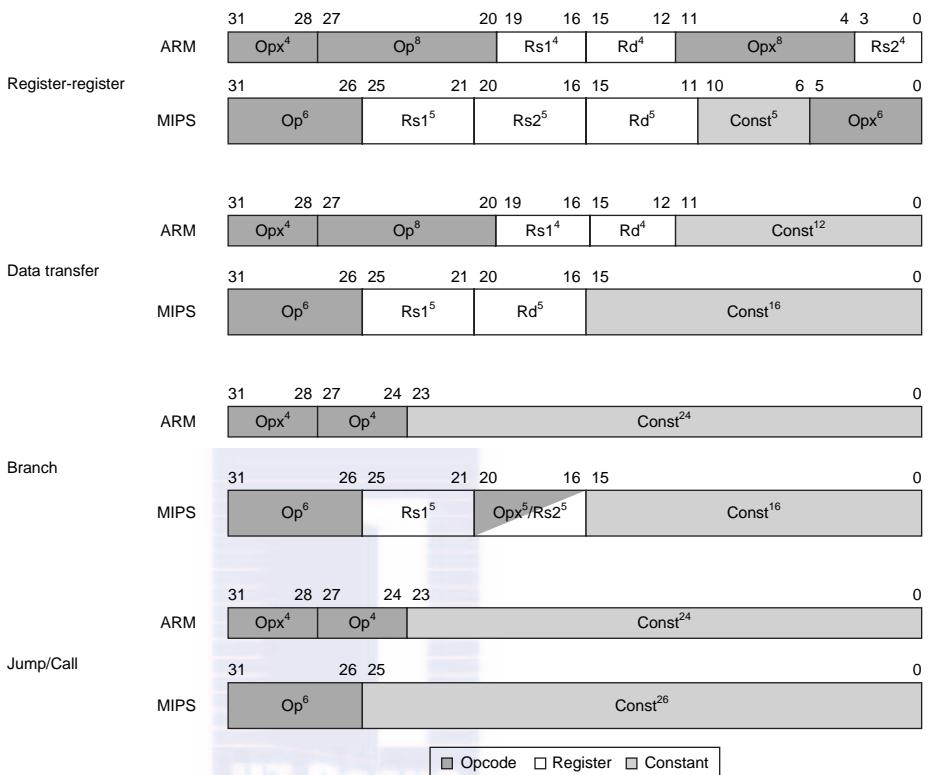


FIGURE 2.34 Instruction formats, ARM, and MIPS. The differences result from whether the architecture has 16 or 32 registers.

Unique Features of ARM

Figure 2.35 shows a few arithmetic-logical instructions not found in MIPS. Since it does not have a dedicated register for 0, it has separate opcodes to perform some operations that MIPS can do with \$zero. In addition, ARM has support for multiword arithmetic.

ARM's 12-bit immediate field has a novel interpretation. The eight least-significant bits are zero-extended to a 32-bit value, then rotated right the number of bits specified in the first four bits of the field multiplied by two. One advantage is that this scheme can represent all powers of two in a 32-bit word. Whether this split actually catches more immediates than a simple 12-bit field would be an interesting study.

Operand shifting is not limited to immediates. The second register of all arithmetic and logical processing operations has the option of being shifted before being operated on. The shift options are shift left logical, shift right logical, shift right arithmetic, and rotate right.

Name	Definition	ARM v.4	MIPS
Load immediate	$Rd = Imm$	mov	addi, \$0,
Not	$Rd = \sim(Rs1)$	mvn	nor, \$0,
Move	$Rd = Rs1$	mov	or, \$0,
Rotate right	$Rd = Rs i >> i$ $Rd_{0...i-1} = Rs_{31-i...31}$	ror	
And not	$Rd = Rs1 \& \sim(Rs2)$	bic	
Reverse subtract	$Rd = Rs2 - Rs1$	rsb, rsc	
Support for multiword integer add	CarryOut, $Rd = Rd + Rs1 + OldCarryOut$	adcs	—
Support for multiword integer sub	CarryOut, $Rd = Rd - Rs1 + OldCarryOut$	sbc	—

FIGURE 2.35 ARM arithmetic/logical instructions not found in MIPS.

ARM also has instructions to save groups of registers, called *block loads and stores*. Under control of a 16-bit mask within the instructions, any of the 16 registers can be loaded or stored into memory in a single instruction. These instructions can save and restore registers on procedure entry and return. These instructions can also be used for block memory copy, and today block copies are the most important use of this instruction.

2.17

Real Stuff: x86 Instructions

Designers of instruction sets sometimes provide more powerful operations than those found in ARM and MIPS. The goal is generally to reduce the number of instructions executed by a program. The danger is that this reduction can occur at the cost of simplicity, increasing the time a program takes to execute because the instructions are slower. This slowness may be the result of a slower clock cycle time or of requiring more clock cycles than a simpler sequence.

The path toward operation complexity is thus fraught with peril. To avoid these problems, designers have moved toward simpler instructions. Section 2.18 demonstrates the pitfalls of complexity.

Evolution of the Intel x86

ARM and MIPS were the vision of single small groups in 1985; the pieces of these architectures fit nicely together, and the whole architecture can be described succinctly. Such is not the case for the x86; it is the product of several independent groups who evolved the architecture over 30 years, adding new features to the original instruction set as someone might add clothing to a packed bag. Here are important x86 milestones.

*Beauty is altogether in
the eye of the beholder.*

Margaret Wolfe
Hungerford, *Molly Bawn*,
1877

general-purpose register (GPR) A register that can be used for addresses or for data with virtually any instruction.

- **1978:** The Intel 8086 architecture was announced as an assembly language-compatible extension of the then successful Intel 8080, an 8-bit microprocessor. The 8086 is a 16-bit architecture, with all internal registers 16 bits wide. Unlike MIPS, the registers have dedicated uses, and hence the 8086 is not considered a general-purpose register architecture.
- **1980:** The Intel 8087 floating-point coprocessor is announced. This architecture extends the 8086 with about 60 floating-point instructions. Instead of using registers, it relies on a stack (see  [Section 2.20](#) and [Section 3.7](#)).
- **1982:** The 80286 extended the 8086 architecture by increasing the address space to 24 bits, by creating an elaborate memory-mapping and protection model (see Chapter 5), and by adding a few instructions to round out the instruction set and to manipulate the protection model.
- **1985:** The 80386 extended the 80286 architecture to 32 bits. In addition to a 32-bit architecture with 32-bit registers and a 32-bit address space, the 80386 added new addressing modes and additional operations. The added instructions make the 80386 nearly a general-purpose register machine. The 80386 also added paging support in addition to segmented addressing (see Chapter 5). Like the 80286, the 80386 has a mode to execute 8086 programs without change.
- **1989–95:** The subsequent 80486 in 1989, Pentium in 1992, and Pentium Pro in 1995 were aimed at higher performance, with only four instructions added to the user-visible instruction set: three to help with multiprocessing (Chapter 7) and a conditional move instruction.
- **1997:** After the Pentium and Pentium Pro were shipping, Intel announced that it would expand the Pentium and the Pentium Pro architectures with MMX (Multi Media Extensions). This new set of 57 instructions uses the floating-point stack to accelerate multimedia and communication applications. MMX instructions typically operate on multiple short data elements at a time, in the tradition of single instruction, multiple data (SIMD) architectures (see Chapter 7). Pentium II did not introduce any new instructions.
- **1999:** Intel added another 70 instructions, labeled SSE (Streaming SIMD Extensions) as part of Pentium III. The primary changes were to add eight separate registers, double their width to 128 bits, and add a single precision floating-point data type. Hence, four 32-bit floating-point operations can be performed in parallel. To improve memory performance, SSE includes cache prefetch instructions plus streaming store instructions that bypass the caches and write directly to memory.
- **2001:** Intel added yet another 144 instructions, this time labeled SSE2. The new data type is double precision arithmetic, which allows pairs of 64-bit floating-point operations in parallel. Almost all of these 144 instructions are

versions of existing MMX and SSE instructions that operate on 64 bits of data in parallel. Not only does this change enable more multimedia operations, it gives the compiler a different target for floating-point operations than the unique stack architecture. Compilers can choose to use the eight SSE registers as floating-point registers like those found in other computers. This change boosted the floating-point performance of the Pentium 4, the first microprocessor to include SSE2 instructions.

- **2003:** A company other than Intel enhanced the x86 architecture this time. AMD announced a set of architectural extensions to increase the address space from 32 to 64 bits. Similar to the transition from a 16- to 32-bit address space in 1985 with the 80386, AMD64 widens all registers to 64 bits. It also increases the number of registers to 16 and increases the number of 128-bit SSE registers to 16. The primary ISA change comes from adding a new mode called *long mode* that redefines the execution of all x86 instructions with 64-bit addresses and data. To address the larger number of registers, it adds a new prefix to instructions. Depending how you count, long mode also adds four to ten new instructions and drops 27 old ones. PC-relative data addressing is another extension. AMD64 still has a mode that is identical to x86 (*legacy mode*) plus a mode that restricts user programs to x86 but allows operating systems to use AMD64 (*compatibility mode*). These modes allow a more graceful transition to 64-bit addressing than the HP/Intel IA-64 architecture.
- **2004:** Intel capitulates and embraces AMD64, relabeling it Extended Memory 64 Technology (EM64T). The major difference is that Intel added a 128-bit atomic compare and swap instruction, which probably should have been included in AMD64. At the same time, Intel announced another generation of media extensions. SSE3 adds 13 instructions to support complex arithmetic, graphics operations on arrays of structures, video encoding, floating-point conversion, and thread synchronization (see Section 2.11). AMD will offer SSE3 in subsequent chips and it will almost certainly add the missing atomic swap instruction to AMD64 to maintain binary compatibility with Intel.
- **2006:** Intel announces 54 new instructions as part of the SSE4 instruction set extensions. These extensions perform tweaks like sum of absolute differences, dot products for arrays of structures, sign or zero extension of narrow data to wider sizes, population count, and so on. They also added support for virtual machines (see Chapter 5).
- **2007:** AMD announces 170 instructions as part of SSE5, including 46 instructions of the base instruction set that adds three operand instructions like MIPS.
- **2008:** Intel announces the Advanced Vector Extension that expands the SSE register width from 128 to 256 bits, thereby redefining about 250 instructions and adding 128 new instructions.

This history illustrates the impact of the “golden handcuffs” of compatibility on the x86, as the existing software base at each step was too important to jeopardize with significant architectural changes. If you looked over the life of the x86, on average the architecture has been extended by one instruction per month!

Whatever the artistic failures of the x86, keep in mind that there are more instances of this architectural family on desktop computers than of any other architecture, increasing by more than 250 million per year. Nevertheless, this checkered ancestry has led to an architecture that is difficult to explain and impossible to love.

Brace yourself for what you are about to see! Do *not* try to read this section with the care you would need to write x86 programs; the goal instead is to give you familiarity with the strengths and weaknesses of the world’s most popular desktop architecture.

Rather than show the entire 16-bit and 32-bit instruction set, in this section we concentrate on the 32-bit subset that originated with the 80386, as this portion of the architecture is what is used today. We start our explanation with the registers and addressing modes, move on to the integer operations, and conclude with an examination of instruction encoding.

x86 Registers and Data Addressing Modes

The registers of the 80386 show the evolution of the instruction set (Figure 2.36). The 80386 extended all 16-bit registers (except the segment registers) to 32 bits, prefixing an *E* to their name to indicate the 32-bit version. We’ll refer to them generically as GPRs (general-purpose registers). The 80386 contains only eight GPRs. This means MIPS programs can use four times as many and ARM twice as many.

Figure 2.37 shows the arithmetic, logical, and data transfer instructions are two-operand instructions. There are two important differences here. The x86 arithmetic and logical instructions must have one operand act as both a source and a destination; ARM and MIPS allow separate registers for source and destination. This restriction puts more pressure on the limited registers, since one source register must be modified. The second important difference is that one of the operands can be in memory. Thus, virtually any instruction may have one operand in memory, unlike ARM and MIPS.

Data memory-addressing modes, described in detail below, offer two sizes of addresses within the instruction. These so-called *displacements* can be 8 bits or 32 bits.

Although a memory operand can use any addressing mode, there are restrictions on which *registers* can be used in a mode. Figure 2.38 shows the x86 addressing modes and which GPRs cannot be used with each mode, as well as how to get the same effect using MIPS instructions.

x86 Integer Operations

The 8086 provides support for both 8-bit (*byte*) and 16-bit (*word*) data types. The 80386 adds 32-bit addresses and data (*double words*) in the x86. (AMD64 adds 64-bit addresses and data, called *quad words*; we’ll stick to the 80386 in this section.) The data type distinctions apply to register operations as well as memory accesses.

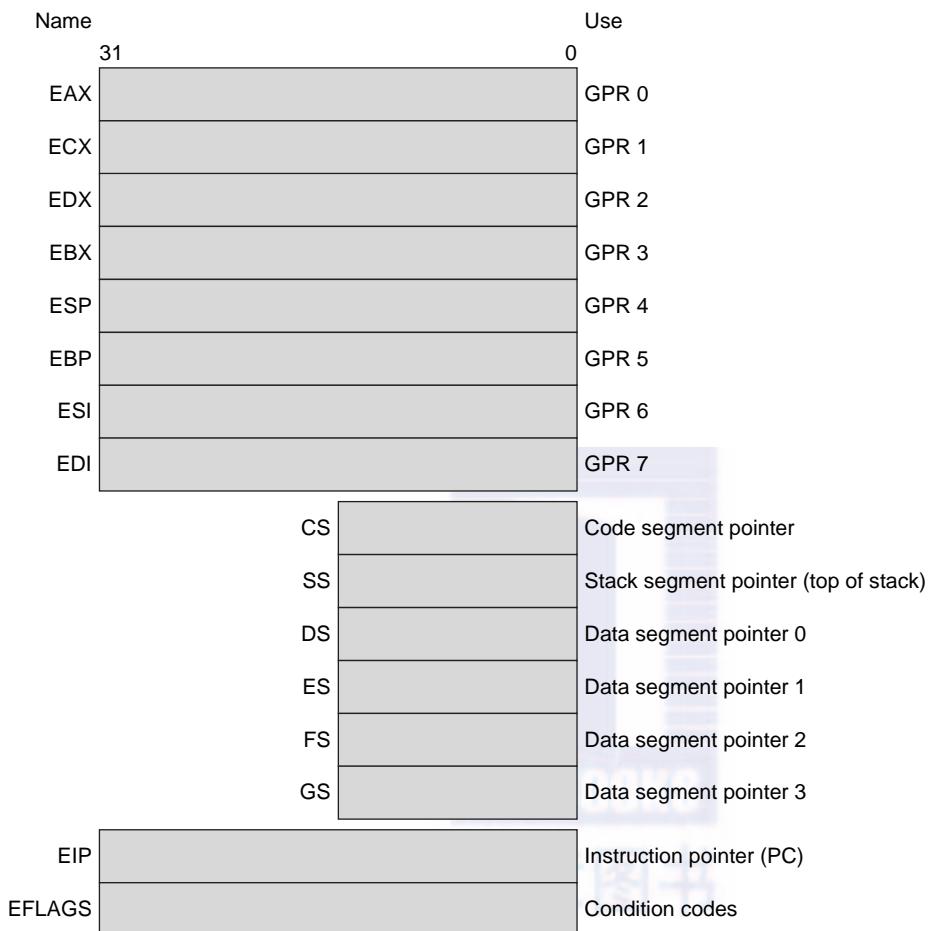


FIGURE 2.36 The 80386 register set. Starting with the 80386, the top eight registers were extended to 32 bits and could also be used as general-purpose registers.

Source/destination operand type	Second source operand
Register	Register
Register	Immediate
Register	Memory
Memory	Register
Memory	Immediate

FIGURE 2.37 Instruction types for the arithmetic, logical, and data transfer instructions.

The x86 allows the combinations shown. The only restriction is the absence of a memory-memory mode. Immediate may be 8, 16, or 32 bits in length; a register is any one of the 14 major registers in Figure 2.36 (not EIP or EFLAGS).

Mode	Description	Register restrictions	MIPS equivalent
Register indirect	Address is in a register .	Not ESP or EBP	<code>lw \$s0,0(\$s1)</code>
Based mode with 8- or 32-bit displacement	Address is contents of base register plus displacement.	Not ESP	<code>lw \$s0,100(\$s1) #<= 16-bit # displacement</code>
Base plus scaled index	The address is $\text{Base} + (2^{\text{Scale}} \times \text{Index})$ where Scale has the value 0, 1, 2, or 3.	Base: any GPR Index: not ESP	<code>mul \$t0,\$s2,4 add \$t0,\$t0,\$s1 lw \$s0,0(\$t0)</code>
Base plus scaled index with 8- or 32-bit displacement	The address is $\text{Base} + (2^{\text{Scale}} \times \text{Index}) + \text{displacement}$ where Scale has the value 0, 1, 2, or 3.	Base: any GPR Index: not ESP	<code>mul \$t0,\$s2,4 add \$t0,\$t0,\$s1 lw \$s0,100(\$t0) # 16-bit # displacement</code>

FIGURE 2.38 x86 32-bit addressing modes with register restrictions and the equivalent MIPS code. The Base plus Scaled Index addressing mode, not found in ARM or MIPS, is included to avoid the multiplies by 4 (scale factor of 2) to turn an index in a register into a byte address (see Figures 2.25 and 2.27). A scale factor of 1 is used for 16-bit data, and a scale factor of 3 for 64-bit data. A scale factor of 0 means the address is not scaled. If the displacement is longer than 16 bits in the second or fourth modes, then the MIPS equivalent mode would need two more instructions: a `lui` to load the upper 16 bits of the displacement and an `add` to sum the upper address with the base register `$s1`. (Intel gives two different names to what is called Based addressing mode—Based and Indexed—but they are essentially identical and we combine them here.)

Almost every operation works on both 8-bit data and on one longer data size. That size is determined by the mode and is either 16 bits or 32 bits.

Clearly, some programs want to operate on data of all three sizes, so the 80386 architects provided a convenient way to specify each version without expanding code size significantly. They decided that either 16-bit or 32-bit data dominates most programs, and so it made sense to be able to set a default large size. This default data size is set by a bit in the code segment register. To override the default data size, an 8-bit *prefix* is attached to the instruction to tell the machine to use the other large size for this instruction.

The prefix solution was borrowed from the 8086, which allows multiple prefixes to modify instruction behavior. The three original prefixes override the default segment register, lock the bus to support synchronization (see Section 2.11), or repeat the following instruction until the register ECX counts down to 0. This last prefix was intended to be paired with a byte move instruction to move a variable number of bytes. The 80386 also added a prefix to override the default address size.

The x86 integer operations can be divided into four major classes:

1. Data movement instructions, including move, push, and pop
2. Arithmetic and logic instructions, including test, integer, and decimal arithmetic operations
3. Control flow, including conditional branches, unconditional jumps, calls, and returns
4. String instructions, including string move and string compare

The first two categories are unremarkable, except that the arithmetic and logic instruction operations allow the destination to be either a register or a memory location. Figure 2.39 shows some typical x86 instructions and their functions.

Instruction	Function
je name	if equal(condition code) {EIP=name}; EIP-128 <= name < EIP+128
jmp name	EIP=name
call name	SP=SP-4; M[SP]=EIP+5; EIP=name;
movw EBX,[EDI+45]	EBX=M[EDI+45]
push ESI	SP=SP-4; M[SP]=ESI
pop EDI	EDI=M[SP]; SP=SP+4
add EAX,#6765	EAX= EAX+6765
test EDX,#42	Set condition code (flags) with EDX and 42
movsl	M[EDI]=M[ESI]; EDI=EDI+4; ESI=ESI+4

FIGURE 2.39 Some typical x86 instructions and their functions. A list of frequent operations appears in Figure 2.40. The CALL saves the EIP of the next instruction on the stack. (EIP is the Intel PC.)

Conditional branches on the x86 are based on *condition codes* or *flags*, like ARM. Condition codes are set as a side effect of an operation; most are used to compare the value of a result to 0. Branches then test the condition codes. PC-relative branch addresses must be specified in the number of bytes, since unlike ARM and MIPS, 80386 instructions are not all 4 bytes in length.

String instructions are part of the 8080 ancestry of the x86 and are not commonly executed in most programs. They are often slower than equivalent software routines (see the fallacy on page 174).

Figure 2.40 lists some of the integer x86 instructions. Many of the instructions are available in both byte and word formats.

x86 Instruction Encoding

Saving the worst for last, the encoding of instructions in the 80386 is complex, with many different instruction formats. Instructions for the 80386 may vary from 1 byte, when there are no operands, up to 15 bytes.

Figure 2.41 shows the instruction format for several of the example instructions in Figure 2.39. The opcode byte usually contains a bit saying whether the operand is 8 bits or 32 bits. For some instructions, the opcode may include the addressing mode and the register; this is true in many instructions that have the form “register = register op immediate.” Other instructions use a “postbyte” or extra opcode byte, labeled “mod, reg, r/m,” which contains the addressing mode information. This postbyte is used for many of the instructions that address memory. The base plus scaled index mode uses a second postbyte, labeled “sc, index, base.”

Instruction	Meaning
Control	Conditional and unconditional branches
jnz, jz	Jump if condition to EIP + 8-bit offset; JNE (for JNZ), JE (for JZ) are alternative names
jmp	Unconditional jump—8-bit or 16-bit offset
call	Subroutine call—16-bit offset; return address pushed onto stack
ret	Pops return address from stack and jumps to it
loop	Loop branch—decrement ECX; jump to EIP + 8-bit displacement if ECX ≠ 0
Data transfer	Move data between registers or between register and memory
move	Move between two registers or between register and memory
push, pop	Push source operand on stack; pop operand from stack top to a register
les	Load ES and one of the GPRs from memory
Arithmetic, logical	Arithmetic and logical operations using the data registers and memory
add, sub	Add source to destination; subtract source from destination; register-memory format
cmp	Compare source and destination; register-memory format
shl, shr, rcr	Shift left; shift logical right; rotate right with carry condition code as flag
cbw	Convert byte in eight rightmost bits of EAX to 16-bit word in right of EAX
test	Logical AND of source and destination sets condition codes
inc, dec	Increment destination, decrement destination
or, xor	Logical OR; exclusive OR; register-memory format
String	Move between string operands; length given by a repeat prefix
movs	Copies from string source to destination by incrementing ESI and EDI; may be repeated
lod\$	Loads a byte, word, or double word of a string into the EAX register

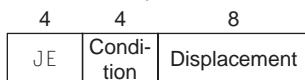
FIGURE 2.40 Some typical operations on the x86. Many operations use register-memory format, where either the source or the destination may be memory and the other may be a register or immediate operand.

Figure 2.42 shows the encoding of the two postbyte address specifiers for both 16-bit and 32-bit mode. Unfortunately, to understand fully which registers and which addressing modes are available, you need to see the encoding of all addressing modes and sometimes even the encoding of the instructions.

x86 Conclusion

Intel had a 16-bit microprocessor two years before its competitors' more elegant architectures, such as the Motorola 68000, and this head start led to the selection of the 8086 as the CPU for the IBM PC. Intel engineers generally acknowledge that the x86 is more difficult to build than computers like ARM and MIPS, but the large

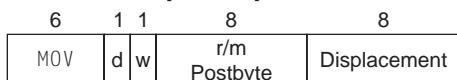
a. JE EIP + displacement



b. CALL



c. MOV EBX, [EDI + 45]



d. PUSH ESI



e. ADD EAX, #6765



f. TEST EDX, #42



FIGURE 2.41 Typical x86 instruction formats. Figure 2.42 shows the encoding of the postbyte. Many instructions contain the 1-bit field w, which says whether the operation is a byte or a double word. The d field in MOV is used in instructions that may move to or from memory and shows the direction of the move. The ADD instruction requires 32 bits for the immediate field, because in 32-bit mode, the immediates are either 8 bits or 32 bits. The immediate field in the TEST is 32 bits long because there is no 8-bit immediate for test in 32-bit mode. Overall, instructions may vary from 1 to 17 bytes in length. The long length comes from extra 1-byte prefixes, having both a 4-byte immediate and a 4-byte displacement address, using an opcode of 2 bytes, and using the scaled index mode specifier, which adds another byte.

market means AMD and Intel can afford more resources to help overcome the added complexity. What the x86 lacks in style, it makes up for in quantity, making it beautiful from the right perspective.

Its saving grace is that the most frequently used x86 architectural components are not too difficult to implement, as AMD and Intel have demonstrated by rapidly improving performance of integer programs since 1978. To get that performance, compilers must avoid the portions of the architecture that are hard to implement fast.

reg	w = 0	w = 1		r/m	mod = 0		mod = 1		mod = 2		mod = 3
		16b	32b		16b	32b	16b	32b	16b	32b	
0	AL	AX	EAX	0	addr=BX+SI =EAX	same	same	same	same	same	same
1	CL	CX	ECX	1	addr=BX+DI =ECX	addr as	addr as	addr as	addr as	addr as	as
2	DL	DX	EDX	2	addr=BP+SI =EDX	mod=0	mod=0	mod=0	mod=0	mod=0	reg
3	BL	BX	EBX	3	addr=BP+SI =EBX	+ disp8	+ disp8	+ disp16	+ disp32	+ disp32	field
4	AH	SP	ESP	4	addr=SI =(sib)	SI+disp8	(sib)+disp8	SI+disp8	(sib)+disp32	(sib)+disp32	"
5	CH	BP	EBP	5	addr=DI =disp32	DI+disp8	EBP+disp8	DI+disp16	EBP+disp32	EBP+disp32	"
6	DH	SI	ESI	6	addr=disp16 =ESI	BP+disp8	ESI+disp8	BP+disp16	ESI+disp32	ESI+disp32	"
7	BH	DI	EDI	7	addr=BX =EDI	BX+disp8	EDI+disp8	BX+disp16	EDI+disp32	EDI+disp32	"

FIGURE 2.42 The encoding of the first address specifier of the x86: mod, reg, r/m. The first four columns show the encoding of the 3-bit reg field, which depends on the w bit from the opcode and whether the machine is in 16-bit mode (8086) or 32-bit mode (80386). The remaining columns explain the mod and r/m fields. The meaning of the 3-bit r/m field depends on the value in the 2-bit mod field and the address size. Basically, the registers used in the address calculation are listed in the sixth and seventh columns, under mod = 0, with mod = 1 adding an 8-bit displacement and mod = 2 adding a 16-bit or 32-bit displacement, depending on the address mode. The exceptions are 1) r/m = 6 when mod = 1 or mod = 2 in 16-bit mode selects BP plus the displacement; 2) r/m = 5 when mod = 1 or mod = 2 in 32-bit mode selects EBP plus displacement; and 3) r/m = 4 in 32-bit mode when mod does not equal 3, where (sib) means use the scaled index mode shown in Figure 2.38. When mod = 3, the r/m field indicates a register, using the same encoding as the reg field combined with the w bit.

2.18 Fallacies and Pitfalls

Fallacy: More powerful instructions mean higher performance.

Part of the power of the Intel x86 is the prefixes that can modify the execution of the following instruction. One prefix can repeat the following instruction until a counter counts down to 0. Thus, to move data in memory, it would seem that the natural instruction sequence is to use move with the repeat prefix to perform 32-bit memory-to-memory moves.

An alternative method, which uses the standard instructions found in all computers, is to load the data into the registers and then store the registers back to memory. This second version of this program, with the code replicated to reduce loop overhead, copies at about 1.5 times faster. A third version, which uses the larger floating-point registers instead of the integer registers of the x86, copies at about 2.0 times faster than the complex move instruction.

Fallacy: Write in assembly language to obtain the highest performance.

At one time compilers for programming languages produced naïve instruction sequences; the increasing sophistication of compilers means the gap between compiled code and code produced by hand is closing fast. In fact, to compete with current compilers, the assembly language programmer needs to understand the concepts in Chapters 4 and 5 thoroughly (processor pipelining and memory hierarchy).

This battle between compilers and assembly language coders is one situation in which humans are losing ground. For example, C offers the programmer a chance to give a hint to the compiler about which variables to keep in registers versus spilled to memory. When compilers were poor at register allocation, such hints were vital to performance. In fact, some old C textbooks spent a fair amount of time giving examples that effectively use register hints. Today's C compilers generally ignore such hints, because the compiler does a better job at allocation than the programmer does.

Even if writing by hand resulted in faster code, the dangers of writing in assembly language are the longer time spent coding and debugging, the loss in portability, and the difficulty of maintaining such code. One of the few widely accepted axioms of software engineering is that coding takes longer if you write more lines, and it clearly takes many more lines to write a program in assembly language than in C or Java. Moreover, once it is coded, the next danger is that it will become a popular program. Such programs always live longer than expected, meaning that someone will have to update the code over several years and make it work with new releases of operating systems and new models of machines. Writing in higher-level language instead of assembly language not only allows future compilers to tailor the code to future machines, it also makes the software easier to maintain and allows the program to run on more brands of computers.

Fallacy: The importance of commercial binary compatibility means successful instruction sets don't change.

While backwards binary compatibility is sacrosanct, Figure 2.43 shows that the x86 architecture has grown dramatically. The average is more than one instruction per month over its 30-year lifetime!

Pitfall: Forgetting that sequential word addresses in machines with byte addressing do not differ by one.

Many an assembly language programmer has toiled over errors made by assuming that the address of the next word can be found by incrementing the address in a register by one instead of by the word size in bytes. Forewarned is forearmed!

Pitfall: Using a pointer to an automatic variable outside its defining procedure.

A common mistake in dealing with pointers is to pass a result from a procedure that includes a pointer to an array that is local to that procedure. Following the stack discipline in Figure 2.12, the memory that contains the local array will be reused as soon as the procedure returns. Pointers to automatic variables can lead to chaos.

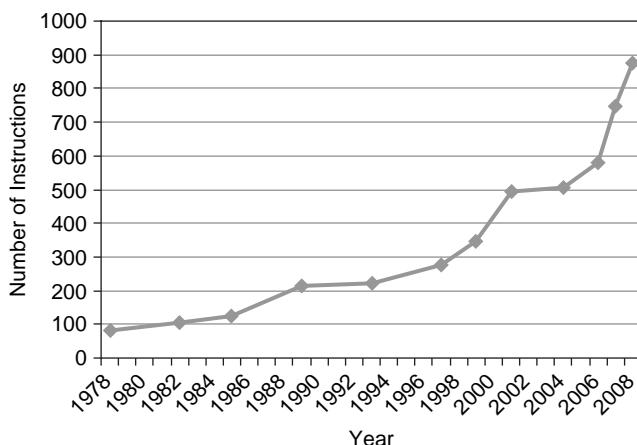


FIGURE 2.43 Growth of x86 instruction set over time. While there is clear technical value to some of these extensions, this rapid change also increases the difficulty for other companies to try to build compatible processors.

Less is more.

Robert Browning,
Andrea del Sarto, 1855

2.19

Concluding Remarks

The two principles of the *stored-program* computer are the use of instructions that are indistinguishable from numbers and the use of alterable memory for programs. These principles allow a single machine to aid environmental scientists, financial advisers, and novelists in their specialties. The selection of a set of instructions that the machine can understand demands a delicate balance among the number of instructions needed to execute a program, the number of clock cycles needed by an instruction, and the speed of the clock. As illustrated in this chapter, four design principles guide the authors of instruction sets in making that delicate balance:

1. *Simplicity favors regularity.* Regularity motivates many features of the MIPS instruction set: keeping all instructions a single size, always requiring three register operands in arithmetic instructions, and keeping the register fields in the same place in each instruction format.
2. *Smaller is faster.* The desire for speed is the reason that MIPS has 32 registers rather than many more.

3. *Make the common case fast.* Examples of making the common MIPS case fast include PC-relative addressing for conditional branches and immediate addressing for larger constant operands.
4. *Good design demands good compromises.* One MIPS example was the compromise between providing for larger addresses and constants in instructions and keeping all instructions the same length.

Above this machine level is assembly language, a language that humans can read. The assembler translates it into the binary numbers that machines can understand, and it even “extends” the instruction set by creating symbolic instructions that aren’t in the hardware. For instance, constants or addresses that are too big are broken into properly sized pieces, common variations of instructions are given their own name, and so on. Figure 2.44 lists the MIPS instructions we have covered so far, both real and pseudoinstructions.

Each category of MIPS instructions is associated with constructs that appear in programming languages:

- The arithmetic instructions correspond to the operations found in assignment statements.
- Data transfer instructions are most likely to occur when dealing with data structures like arrays or structures.
- The conditional branches are used in *if* statements and in loops.
- The unconditional jumps are used in procedure calls and returns and for *case/switch* statements.

These instructions are not born equal; the popularity of the few dominates the many. For example, Figure 2.45 shows the popularity of each class of instructions for SPEC2006. The varying popularity of instructions plays an important role in the chapters about datapath, control, and pipelining.

After we explain computer arithmetic in Chapter 3, we reveal the rest of the MIPS instruction set architecture.

MIPS instructions	Name	Format	Pseudo MIPS	Name	Format
add	add	R	move	move	R
subtract	sub	R	multiply	mult	R
add immediate	addi	I	multiply immediate	multi	I
load word	lw	I	load immediate	li	I
store word	sw	I	branch less than	blt	I
load half	lh	I	branch less than or equal	ble	I
load half unsigned	lhu	I			
store half	sh	I	branch greater than	bgt	I
load byte	lb	I	branch greater than or equal	bge	I
load byte unsigned	lbu	I			
store byte	sb	I			
load linked	ll	I			
store conditional	sc	I			
load upper immediate	lui	I			
and	and	R			
or	or	R			
nor	nor	R			
and immediate	andi	I			
or immediate	ori	I			
shift left logical	sll	R			
shift right logical	srl	R			
branch on equal	beq	I			
branch on not equal	bne	I			
set less than	slt	R			
set less than immediate	slti	I			
set less than immediate unsigned	sltiu	I			
jump	j	J			
jump register	jr	R			
jump and link	jal	J			

FIGURE 2.44 The MIPS instruction set covered so far, with the real MIPS instructions on the left and the pseudoinstructions on the right. Appendix B (Section B.10) describes the full MIPS architecture. Figure 2.1 shows more details of the MIPS architecture revealed in this chapter. The information given here is also found in Columns 1 and 2 of the MIPS Reference Data Card at the front of the book.

Instruction class	MIPS examples	HLL correspondence	Frequency	
			Integer	Ft. pt.
Arithmetic	add, sub, addi	Operations in assignment statements	16%	48%
Data transfer	lw, sw, lb, lbu, lh, lhu, sb, lui	References to data structures, such as arrays	35%	36%
Logical	and, or, nor, andi, ori, sll, srl	Operations in assignment statements	12%	4%
Conditional branch	beq, bne, slt, slti, sltiu	If statements and loops	34%	8%
Jump	j, jr, jal	Procedure calls, returns, and case/switch statements	2%	0%

FIGURE 2.45 MIPS instruction classes, examples, correspondence to high-level program language constructs, and percentage of MIPS instructions executed by category for the average SPEC2006 benchmarks. Figure 3.26 in Chapter 3 shows average percentage of the individual MIPS instructions executed.



Historical Perspective and Further Reading

This section surveys the history of instruction set architectures (ISAs) over time, and we give a short history of programming languages and compilers. ISAs include accumulator architectures, general-purpose register architectures, stack architectures, and a brief history of ARM and the x86. We also review the controversial subjects of high-level-language computer architectures and reduced instruction set computer architectures. The history of programming languages includes Fortran, Lisp, Algol, C, Cobol, Pascal, Simula, Smalltalk, C++, and Java, and the history of compilers includes the key milestones and the pioneers who achieved them. The rest of this section is on the CD.



Exercises

Contributed by John Oliver of Cal Poly, San Luis Obispo, with contributions from Nicole Kaiyan (University of Adelaide) and Milos Prvulovic (Georgia Tech)

Appendix B describes the MIPS simulator, which is helpful for these exercises. Although the simulator accepts pseudoinstructions, try not to use pseudoinstructions for any exercises that ask you to produce MIPS code. Your goal should be to learn the real MIPS instruction set, and if you are asked to count instructions, your count should reflect the actual instructions that will be executed and not the pseudoinstructions.

There are some cases where pseudoinstructions must be used (for example, the `la` instruction when an actual value is not known at assembly time). In many cases,

they are quite convenient and result in more readable code (for example, the `li` and `move` instructions). If you choose to use pseudoinstructions for these reasons, please add a sentence or two to your solution stating which pseudoinstructions you have used and why.

Exercise 2.1

The following problems deal with translating from C to MIPS. Assume that the variables `g`, `h`, `i`, and `j` are given and could be considered 32-bit integers as declared in a C program.

a.	<code>f = g + h + i + j;</code>
b.	<code>f = g + (h + 5);</code>

2.1.1 [5] <2.2> For the C statements above, what is the corresponding MIPS assembly code? Use a minimal number of MIPS assembly instructions.

2.1.2 [5] <2.2> For the C statements above, how many MIPS assembly instructions are needed to perform the C statement?

2.1.3 [5] <2.2> If the variables `f`, `g`, `h`, `i`, and `j` have values 1, 2, 3, 4, and 5, respectively, what is the end value of `f`?

The following problems deal with translating from MIPS to C. Assume that the variables `g`, `h`, `i`, and `j` are given and could be considered 32-bit integers as declared in a C program.

a.	<code>add f, g, h</code>
b.	<code>addi f, f, 1</code> <code>add f, g, h</code>

2.1.4 [5] <2.2> For the MIPS statements above, what is a corresponding C statement?

2.1.5 [5] <2.2> If the variables `f`, `g`, `h`, and `i` have values 1, 2, 3, and 4, respectively, what is the end value of `f`?

Exercise 2.2

The following problems deal with translating from C to MIPS. Assume that the variables `g`, `h`, `i`, and `j` are given and could be considered 32-bit integers as declared in a C program.

a.	$f = f + f + i;$
b.	$f = g + (j + 2);$

2.2.1 [5] <2.2> For the C statements above, what is the corresponding MIPS assembly code? Use a minimal number of MIPS assembly instructions.

2.2.2 [5] <2.2> For the C statements above, how many MIPS assembly instructions are needed to perform the C statement?

2.2.3 [5] <2.2> If the variables f , g , h , and i have values 1, 2, 3, and 4, respectively, what is the end value of f ?

The following problems deal with translating from MIPS to C. For the following exercise, assume that the variables g , h , i , and j are given and could be considered 32-bit integers as declared in a C program.

a.	add f, f, h
b.	sub f, \$0, f addi f, f, 1

2.2.4 [5] <2.2> For the MIPS statements above, what is a corresponding C statement?

2.2.5 [5] <2.2> If the variables f , g , h , and i have values 1, 2, 3, and 4, respectively, what is the end value of f ?

Exercise 2.3

The following problems deal with translating from C to MIPS. Assume that the variables g , h , i , and j are given and could be considered 32-bit integers as declared in a C program.

a.	$f = f + g + h + i + j + 2;$
b.	$f = g - (f + 5);$

2.3.1 [5] <2.2> For the C statements above, what is the corresponding MIPS assembly code? Use a minimal number of MIPS assembly instructions.

2.3.2 [5] <2.2> For the C statements above, how many MIPS assembly instructions are needed to perform the C statement?

2.3.3 [5] <2.2> If the variables f, g, h, i, and j have values 1, 2, 3, 4, and 5, respectively, what is the end value of f?

The following problems deal with translating from MIPS to C. Assume that the variables g, h, i, and j are given and could be considered 32-bit integers as declared in a C program.

a.	add f, -g, h
b.	addi h, f, 1 sub f, g, h

2.3.4 [5] <2.2> For the MIPS statements above, what is a corresponding C statement?

2.3.5 [5] <2.2> If the variables f, g, h, and i have values 1, 2, 3, and 4, respectively, what is the end value of f?

Exercise 2.4

The following problems deal with translating from C to MIPS. Assume that the variables f, g, h, i, and j are assigned to registers \$s0, \$s1, \$s2, \$s3, and \$s4, respectively. Assume that the base address of the arrays A and B are in registers \$s6 and \$s7, respectively.

a.	f = g + h + B[4];
b.	f = g - A[B[4]];

2.4.1 [10] <2.2, 2.3> For the C statements above, what is the corresponding MIPS assembly code?

2.4.2 [5] <2.2, 2.3> For the C statements above, how many MIPS assembly instructions are needed to perform the C statement?

2.4.3 [5] <2.2, 2.3> For the C statements above, how many different registers are needed to carry out the C statement?

The following problems deal with translating from MIPS to C. Assume that the variables f, g, h, i, and j are assigned to registers \$s0, \$s1, \$s2, \$s3, and \$s4, respectively. Assume that the base address of the arrays A and B are in registers \$s6 and \$s7, respectively.

a.	<pre>add \$s0, \$s0, \$s1 add \$s0, \$s0, \$s2 add \$s0, \$s0, \$s3 add \$s0, \$s0, \$s4</pre>
b.	<code>lw \$s0, 4(\$s6)</code>

2.4.4 [10] <2.2, 2.3> For the MIPS assembly instructions above, what is the corresponding C statement?

2.4.5 [5] <2.2, 2.3> For the MIPS assembly instructions above, rewrite the assembly code to minimize the number of MIPS instructions (if possible) needed to carry out the same function.

2.4.6 [5] <2.2, 2.3> How many registers are needed to carry out the MIPS assembly as written above? If you could rewrite the code above, what is the minimal number of registers needed?

Exercise 2.5

In the following problems, we will be investigating memory operations in the context of a MIPS processor. The table below shows the values of an array stored in memory.

a.	<table> <thead> <tr> <th>Address</th><th>Data</th></tr> </thead> <tbody> <tr> <td>12</td><td>1</td></tr> <tr> <td>8</td><td>6</td></tr> <tr> <td>4</td><td>4</td></tr> <tr> <td>0</td><td>2</td></tr> </tbody> </table>	Address	Data	12	1	8	6	4	4	0	2		
Address	Data												
12	1												
8	6												
4	4												
0	2												
b.	<table> <thead> <tr> <th>Address</th> <th>Data</th> </tr> </thead> <tbody> <tr> <td>16</td> <td>1</td> </tr> <tr> <td>12</td> <td>2</td> </tr> <tr> <td>8</td> <td>3</td> </tr> <tr> <td>4</td> <td>4</td> </tr> <tr> <td>0</td> <td>5</td> </tr> </tbody> </table>	Address	Data	16	1	12	2	8	3	4	4	0	5
Address	Data												
16	1												
12	2												
8	3												
4	4												
0	5												

2.5.1 [10] <2.2, 2.3> For the memory locations in the table above, write C code to sort the data from lowest-to-highest, placing the lowest value in the smallest memory location shown in the figure. Assume that the data shown represents the C variable called `Array`, which is an array of type `int`. Assume that this particular machine is a byte-addressable machine and a word consists of 4 bytes.

2.5.2 [10] <2.2, 2.3> For the memory locations in the table above, write MIPS code to sort the data from lowest-to-highest, placing the lowest value in the smallest memory location. Use a minimum number of MIPS instructions. Assume the base address of `Array` is stored in register `$s6`.

2.5.3 [5] <2.2, 2.3> To sort the array above, how many instructions are required for the MIPS code? If you are not allowed to use the immediate field in `lw` and `sw` instructions, how many MIPS instructions do you need?

The following problems explore the translation of hexadecimal numbers to other number formats.

a.	0x12345678
b.	0xbeadfc00d

2.5.4 [5] <2.3> Translate the hexadecimal numbers above into decimal.

2.5.5 [5] <2.3> Show how the data in the table would be arranged in memory of a little-endian and a big-endian machine. Assume the data is stored starting at address 0.

Exercise 2.6

The following problems deal with translating from C to MIPS. Assume that the variables `f`, `g`, `h`, `i`, and `j` are assigned to registers `$s0`, `$s1`, `$s2`, `$s3`, and `$s4`, respectively. Assume that the base address of the arrays `A` and `B` are in registers `$s6` and `$s7`, respectively.

a.	<code>f = -g + h + B[1];</code>
b.	<code>f = A[B[g]+1];</code>

2.6.1 [10] <2.2, 2.3> For the C statements above, what is the corresponding MIPS assembly code?

2.6.2 [5] <2.2, 2.3> For the C statements above, how many MIPS assembly instructions are needed to perform the C statement?

2.6.3 [5] <2.2, 2.3> For the C statements above, how many registers are needed to carry out the C statement using MIPS assembly code?

The following problems deal with translating from MIPS to C. Assume that the variables `f`, `g`, `h`, `i`, and `j` are assigned to registers `$s0`, `$s1`, `$s2`, `$s3`, and `$s4`, respectively. Assume that the base address of the arrays `A` and `B` are in registers `$s6` and `$s7`, respectively.

a.	add \$s0, \$s0, \$s1 add \$s0, \$s3, \$s2 add \$s0, \$s0, \$s3
b.	addi \$s6, \$s6, -20 add \$s6, \$s6, \$s1 lw \$s0, 8(\$s6)

2.6.4 [5] <2.2, 2.3> For the MIPS assembly instructions above, what is the corresponding C statement?

2.6.5 [5] <2.2, 2.3> For the MIPS assembly above, assume that the registers \$s0, \$s1, \$s2, \$s3, contain the values 10, 20, 30, and 40, respectively. Also, assume that register \$s6 contains the value 256, and that memory contains the following values:

Address	Value
256	100
260	200
264	300

Find the value of \$s0 at the end of the assembly code.

2.6.6 [10] <2.3, 2.5> For each MIPS instruction, show the value of the op, rs, and rt fields. For I-type instructions, show the value of the immediate field, and for the R-type instructions, show the value of the rd field.

Exercise 2.7

The following problems explore number conversions from signed and unsigned binary number to decimal numbers.

a.	1010 1101 0001 0000 0000 0000 0000 0010 _{two}
b.	1111 1111 1111 1111 1011 0011 0101 0011 _{two}

2.7.1 [5] <2.4> For the patterns above, what base 10 number does it represent, assuming that it is a two's complement integer?

2.7.2 [5] <2.4> For the patterns above, what base 10 number does it represent, assuming that it is an unsigned integer?

2.7.3 [5] <2.4> For the patterns above, what hexadecimal number does it represent?

The following problems explore number conversions from decimal to signed and unsigned binary numbers.

a.	2147483647 _{ten}
b.	1000 _{ten}

2.7.4 [5] <2.4> For the base ten numbers above, convert to two's complement binary.

2.7.5 [5] <2.4> For the base ten numbers above, convert to two's complement hexadecimal.

2.7.6 [5] <2.4> For the base ten numbers above, convert the negated values from the table to two's complement hexadecimal.

Exercise 2.8

The following problems deal with sign extension and overflow. Registers \$s0 and \$s1 hold the values as shown in the table below. You will be asked to perform a MIPS operation on these registers and show the result.

a.	\$s0 = 70000000 _{sixteen} , \$s1 = 0xFFFFFFFF _{sixteen}
b.	\$s0 = 0x40000000 _{sixteen} , \$s1 = 0x40000000 _{sixteen}

2.8.1 [5] <2.4> For the contents of registers \$s0 and \$s1 as specified above, what is the value of \$t0 for the following assembly code:

```
add $t0, $s0, $s1
```

Is the result in \$t0 the desired result, or has there been overflow?

2.8.2 [5] <2.4> For the contents of registers \$s0 and \$s1 as specified above, what is the value of \$t0 for the following assembly code:

```
sub $t0, $s0, $s1
```

Is the result in \$t0 the desired result, or has there been overflow?

2.8.3 [5] <2.4> For the contents of registers \$s0 and \$s1 as specified above, what is the value of \$t0 for the following assembly code:

```
add $t0, $s0, $s1
add $t0, $t0, $s0
```

Is the result in \$t0 the desired result, or has there been overflow?

In the following problems, you will perform various MIPS operations on a pair of registers, \$s0 and \$s1. Given the values of \$s0 and \$s1 in each of the questions below, state if there will be overflow.

a.	add \$s0, \$s0, \$s1
b.	sub \$s0, \$s0, \$s1 sub \$s0, \$s0, \$s1

2.8.4 [5] <2.4> Assume that register \$s0 = 0x70000000 and \$s1 = 0x10000000. For the table above, will there be overflow?

2.8.5 [5] <2.4> Assume that register \$s0 = 0x40000000 and \$s1 = 0x20000000. For the table above, will there be overflow?

2.8.6 [5] <2.4> Assume that register \$s0 = 0x8FFFFFFF and \$s1 = 0xD0000000. For the table above, will there be overflow?

Exercise 2.9

The table below contains various values for register \$s1. You will be asked to evaluate if there would be overflow for a given operation.

a.	2147483647 _{ten}
b.	0xD0000000 _{sixteen}

2.9.1 [5] <2.4> Assume that register \$s0 = 0x70000000 and \$s1 has the value as given in the table. If the instruction: add \$s0, \$s0, \$s1 is executed, will there be overflow?

2.9.2 [5] <2.4> Assume that register \$s0 = 0x80000000 and \$s1 has the value as given in the table. If the instruction: sub \$s0, \$s0, \$s1 is executed, will there be overflow?

2.9.3 [5] <2.4> Assume that register \$s0 = 0x7FFFFFFF and \$s1 has the value as given in the table. If the instruction: sub \$s0, \$s0, \$s1 is executed, will there be overflow?

The table below contains various values for register \$s1. You will be asked to evaluate if there would be overflow for a given operation.

a.	1010 1101 0001 0000 0000 0000 0000 0010 _{two}
b.	1111 1111 1111 1111 1011 0011 0101 0011 _{two}

2.9.4 [5] <2.4> Assume that register \$s0 = 0x70000000 and \$s1 has the value as given in the table. If the instruction: add \$s0, \$s0, \$s1 is executed, will there be overflow?

2.9.5 [5] <2.4> Assume that register \$s0 = 0x70000000 and \$s1 has the value as given in the table. If the instruction: add \$s0, \$s0, \$s1 is executed, what is the result in hex?

2.9.6 [5] <2.4> Assume that register \$s0 = 0x70000000 and \$s1 has the value as given in the table. If the instruction: add \$s0, \$s0, \$s1 is executed, what is the result in base ten?

Exercise 2.10

In the following problems, the data table contains bits that represent the opcode of an instruction. You will be asked to translate the entries into assembly code and determine what format of MIPS instruction the bits represent.

a.	1010 1110 0000 1011 0000 0000 0000 0100 _{two}
b.	1000 1101 0000 1000 0000 0000 0100 0000 _{two}

2.10.1 [5] <2.5> For the binary entries above, what instruction do they represent?

2.10.2 [5] <2.5> What type (I-type, R-type) instruction do the binary entries above represent?

2.10.3 [5] <2.4, 2.5> If the binary entries above were data bits, what number would they represent in hexadecimal?

In the following problems, the data table contains MIPS instructions. You will be asked to translate the entries into the bits of the opcode and determine what is the MIPS instruction format.

a.	add \$t0, \$t0, \$zero
b.	lw \$t1, 4(\$s3)

2.10.4 [5] <2.4, 2.5> For the instructions above, show the hexadecimal representation of these instructions.

2.10.5 [5] <2.5> What type (I-type, R-type) instruction do the instructions above represent?

2.10.6 [5] <2.5> What is the hexadecimal representation of the opcode, rs, and rt fields in this instruction? For R-type instructions, what is the hexadecimal representation of the rd and funct fields? For I-type instructions, what is the hexadecimal representation of the immediate field?

Exercise 2.11

In the following problems, the data table contains bits that represent the opcode of an instruction. You will be asked to translate the entries into assembly code and determine what format of MIPS instruction the bits represent.

a.	0xAE0BFFFC
b.	0x8D08FFC0

2.11.1 [5] <2.4, 2.5> What binary number does the above hexadecimal number represent?

2.11.2 [5] <2.4, 2.5> What decimal number does the above hexadecimal number represent?

2.11.3 [5] <2.5> What instruction does the above hexadecimal number represent?

In the following problems, the data table contains the values of various fields of MIPS instructions. You will be asked to determine what the instruction is, and find the MIPS format for the instruction.

a.	op=0, rs=1, rt=2, rd=3, shamt=0, funct=32
b.	op=0x2B, rs=0x10, rt=0x5, const=0x4

2.11.4 [5] <2.5> What type (I-type, R-type) instruction do the instructions above represent?

2.11.5 [5] <2.5> What is the MIPS assembly instruction described above?

2.11.6 [5] <2.4, 2.5> What is the binary representation of the instructions above?

Exercise 2.12

In the following problems, the data table contains various modifications that could be made to the MIPS instruction set architecture. You will investigate the impact of these changes on the instruction format of the MIPS architecture.

a.	8 registers
b.	10 bit immediate constants

2.12.1 [5] <2.5> If the instruction set of the MIPS processor is modified, the instruction format must also be changed. For each of the suggested changes above, show the size of the bit fields of an R-type format instruction. What is the total number of bits needed for each instruction?

2.12.2 [5] <2.5> If the instruction set of the MIPS processor is modified, the instruction format must also be changed. For each of the suggested changes above, show the size of the bit fields of an I-type format instruction. What is the total number of bits needed for each instruction?

2.12.3 [5] <2.5, 2.10> Why could the suggested change in the table above decrease the size of a MIPS assembly program? Why could the suggested change in the table above increase the size of a MIPS assembly program?

In the following problems, the data table contains hexadecimal values. You will be asked to determine what MIPS instruction the value represents, and find the MIPS instruction format.

a.	0x01090010
b.	0x8D090012

2.12.4 [5] <2.5> For the entries above, what is the value of the number in decimal?

2.12.5 [5] <2.5> For the hexadecimal entries above, what instruction do they represent?

2.12.6 [5] <2.4, 2.5> What type (I-type, R-type) instruction do the binary entries above represent? What is the value of the op field and the rt field?

Exercise 2.13

In the following problems, the data table contains the values for registers \$t0 and \$t1. You will be asked to perform several MIPS logical operations on these registers.

a.	\$t0 = 0x55555555, \$t1 = 0x12345678
b.	\$t0 = 0xBEADFEED, \$t1 = 0xDEADFADE

2.13.1 [5] <2.6> For the lines above, what is the value of \$t2 for the following sequence of instructions:

```
sll $t2, $t0, 4
or $t2, $t2, $t1
```

2.13.2 [5] <2.6> For the values in the table above, what is the value of \$t2 for the following sequence of instructions:

```
sll $t2, $t0, 4
andi $t2, $t2, -1
```

2.13.3 [5] <2.6> For the lines above, what is the value of \$t2 for the following sequence of instructions:

```
srl $t2, $t0, 3
andi $t2, $t2, 0xFFEF
```

In the following exercise, the data table contains various MIPS logical operations. You will be asked to find the result of these operations given values for registers \$t0 and \$t1.

a.	sll \$t2, \$t0, 1 or \$t2, \$t2, \$t1
b.	srl \$t2, \$t0, 1 andi \$t2, \$t2, 0x00F0

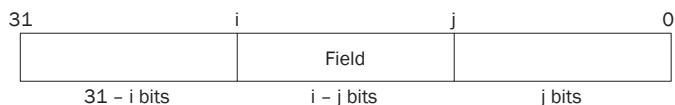
2.13.4 [5] <2.6> Assume that \$t0 = 0x0000A5A5 and \$t1 = 00005A5A. What is the value of \$t2 after the two instructions in the table?

2.13.5 [5] <2.6> Assume that $\$t0 = 0xA5A50000$ and $\$t1 = A5A50000$. What is the value of $\$t2$ after the two instructions in the table?

2.13.6 [5] <2.6> Assume that $\$t0 = 0xA5A5FFFF$ and $\$t1 = A5A5FFFF$. What is the value of $\$t2$ after the two instructions in the table?

Exercise 2.14

The following figure shows the placement of a bit field in register $\$t0$.



In the following problems, you will be asked to write MIPS instructions to extract the bits “Field” from register $\$t0$ and place them into register $\$t1$ at the location indicated in the following table.

a.	31	i - j	
	0 0 0 ... 0 0 0	Field	
b.	31	14 + i - j bits	14 0
	0 0 0 ... 0 0 0	Field	0 0 0 ... 0 0 0

2.14.1 [20] <2.6> Find the shortest sequence of MIPS instructions that extracts a field from $\$t0$ for the constant values $i = 22$ and $j = 5$ and places the field into $\$t1$ in the format shown in the data table.

2.14.2 [5] <2.6> Find the shortest sequence of MIPS instructions that extracts a field from $\$t0$ for the constant values $i = 4$ and $j = 0$ and places the field into $\$t1$ in the format shown in the data table.

2.14.3 [5] <2.6> Find the shortest sequence of MIPS instructions that extracts a field from $\$t0$ for the constant values $i = 31$ and $j = 28$ and places the field into $\$t1$ in the format shown in the data table.

In the following problems, you will be asked to write MIPS instructions to extract the bits “Field” from register $\$t0$ shown in the figure and place them into register $\$t1$ at the location indicated in the following table. The bits shown as “XXX” are to remain unchanged.

a.	31	i - j		
		XXX...XXX	Field	
b.	31	14 + i - j bits	14	0
		XXX...XXX	Field	XXX...XXX

2.14.4 [20] <2.6> Find the shortest sequence of MIPS instructions that extracts a field from \$t0 for the constant values $i = 17$ and $j = 11$ and places the field into \$t1 in the format shown in the data table.

2.14.5 [5] <2.6> Find the shortest sequence of MIPS instructions that extracts a field from \$t0 for the constant values $i = 5$ and $j = 0$ and places the field into \$t1 in the format shown in the data table.

2.14.6 [5] <2.6> Find the shortest sequence of MIPS instructions that extracts a field from \$t0 for the constant values $i = 31$ and $j = 29$ and places the field into \$t1 in the format shown in the data table.

Exercise 2.15

For these problems, the table holds some logical operations that are not included in the MIPS instruction set. How can these instructions be implemented?

a.	andn \$t1, \$t2, \$t3	// bit-wise AND of \$t2, !\$t3
b.	xnor \$t1, \$t2, \$t3	// bit-wise exclusive-NOR

2.15.1 [5] <2.6> The logical instructions above are not included in the MIPS instruction set, but are described above. If the value of \$t2 = 0x00FFA5A5 and the value of \$t3 = 0xFFFF003C, what is the result in \$t1?

2.15.2 [10] <2.6> The logical instructions above are not included in the MIPS instruction set, but can be synthesized using one or more MIPS assembly instructions. Provide a minimal set of MIPS instructions that may be used in place of the instructions in the table above.

2.15.3 [5] <2.6> For your sequence of instructions in 2.15.2, show the bit-level representation of each instruction.

Various C-level logical statements are shown in the table below. In this exercise, you will be asked to evaluate the statements and implement these C statements using MIPS assembly instructions.

a.	$A = B \& C[0];$
b.	$A = A ? B : C[0]$

2.15.4 [5] <2.6> The table above shows different C statements that use logical operators. If the memory location at C[0] contains the integer value 0x00001234, and the initial integer value of A and B are 0x00000000 and 0x00002222, what is the result value of A?

2.15.5 [5] <2.6> For the C statements in the table above, write a minimal sequence of MIPS assembly instructions that does the identical operation.

2.15.6 [5] <2.6> For your sequence of instructions in 2.15.5, show the bit-level representation of each instruction.

Exercise 2.16

For these problems, the table holds various binary values for register \$t0. Given the value of \$t0, you will be asked to evaluate the outcome of different branches.

a.	1010 1101 0001 0000 0000 0000 0000 0010 _{two}
b.	1111 1111 1111 1111 1111 1111 1111 1111 _{two}

2.16.1 [5] <2.7> Suppose that register \$t0 contains a value from above and \$t1 has the value

0011 1111 1111 1000 0000 0000 0000 0000_{two}

What is the value of \$t2 after the following instructions?

```

    slt  $t2, $t0, $t1
    beq  $t2, $zero, ELSE
        j    DONE
    ELSE: addi $t2, $zero, 2
    DONE:
  
```

2.16.2 [5] <2.7> Suppose that register \$t0 contains a value from the table above and is compared against the value X, as used in the MIPS instruction below. For what values of X, if any, will \$t2 be equal to 1?

slti \$t2, \$t0, X

2.16.3 [5] <2.7> Suppose the program counter (PC) is set to 0x0000 0020. Is it possible to use the jump (j) MIPS assembly instruction to set the PC to the

address as shown in the data table above? Is it possible to use the branch-on-equal (beq) MIPS assembly instruction to set the PC to the address as shown in the data table above?

For these problems, the table holds various binary values for register \$t0. Given the value of \$t0, you will be asked to evaluate the outcome of different branches.

a.	0x00001000
b.	0x20001400

2.16.4 [5] <2.7> Suppose that register \$t0 contains a value from above. What is the value of \$t2 after the following instructions?

```

    slt  $t2, $t0, $t0
    bne  $t2, $zero, ELSE
    j    DONE
ELSE: addi $t2, $t2, 2
DONE:

```

2.16.5 [5] <2.6, 2.7> Suppose that register \$t0 contains a value from above. What is the value of \$t2 after the following instructions?

```

    sll $t0, $t0, 2
    slt $t2, $t0, $zero

```

2.16.6 [5] <2.7> Suppose the program counter (PC) is set to 0x2000 0000. Is it possible to use the jump (j) MIPS assembly instruction to set the PC to the address as shown in the data table above? Is it possible to use the branch-on-equal (beq) MIPS assembly instruction to set the PC to the address as shown in the data table above?

Exercise 2.17

For these problems, several instructions that are not included in the MIPS instruction set are shown.

a.	abs \$t2, \$t3 # R[rd] = R[rt]
b.	sgt \$t1, \$t2, \$t3 # R[rd] = (R[rs] > R[rt]) ? 1:0

2.17.1 [5] <2.7> The table above contains some instructions not included in the MIPS instruction set and the description of each instruction. Why are these instructions not included in the MIPS instruction set.

2.17.2 [5] <2.7> The table above contains some instructions not included in the MIPS instruction set and the description of each instruction. If these instructions were to be implemented in the MIPS instruction set, what is the most appropriate instruction format?

2.17.3 [5] <2.7> For each instruction in the table above, find the shortest sequence of MIPS instructions that performs the same operation.

For these problems, the table holds MIPS assembly code fragments. You will be asked to evaluate each of the code fragments, familiarizing you with the different MIPS branch instructions.

a.	<pre> LOOP: slt \$t2, \$0, \$t1 bne \$t2, \$zero, ELSE j DONE ELSE: addi \$s2, \$s2, 2 subi \$t1, \$t1, 1 j LOOP DONE: </pre>
b.	<pre> LOOP: addi \$t2, \$0, 0xA LOOP2: addi \$s2, \$s2, 2 subi \$t2, \$t2, 1 bne \$t2, \$0, LOOP2 subi \$t1, \$t1, 1 bne \$t1, \$0, LOOP DONE: </pre>

2.17.4 [5] <2.7> For the loops written in MIPS assembly above, assume that the register \$t1 is initialized to the value 10. What is the value in register \$s2 assuming the \$s2 is initially zero?

2.17.5 [5] <2.7> For each of the loops above, write the equivalent C code routine. Assume that the registers \$s1, \$s2, \$t1, and \$t2 are integers A, B, i, and temp, respectively.

2.17.6 [5] <2.7> For the loops written in MIPS assembly above, assume that the register \$t1 is initialized to the value N. How many MIPS instructions are executed?

Exercise 2.18

For these problems, the table holds some C code. You will be asked to evaluate these C code statements in MIPS assembly code.

a.	<pre> for(i=0; i<10; i++) a += b; </pre>
b.	<pre> while (a < 10){ D[a] = b + a; a += 1; } </pre>

2.18.1 [5] <2.7> For the table above, draw a control-flow graph of the C code.

2.18.2 [5] <2.7> For the table above, translate the C code to MIPS assembly code. Use a minimum number of instructions. Assume that the value *a*, *b*, *i*, *j* are in registers \$s0, \$s1, \$t0, \$t1, respectively. Also, assume that register \$s2 holds the base address of the array *D*.

2.18.3 [5] <2.7> How many MIPS instructions does it take to implement the C code? If the variables *a* and *b* are initialized to 10 and 1 and all elements of *D* are initially 0, what is the total number of MIPS instructions that is executed to complete the loop?

For these problems, the table holds MIPS assembly code fragments. You will be asked to evaluate each of the code fragments, familiarizing you with the different MIPS branch instructions.

a. addi \$t1, \$0, 100 LOOP: lw \$s1, 0(\$s0) add \$s2, \$s2, \$s1 addi \$s0, \$s0, 4 subi \$t1, \$t1, 1 bne \$t1, \$0, LOOP
b. addi \$t1, \$s0, 400 LOOP: lw \$s1, 0(\$s0) add \$s2, \$s2, \$s1 lw \$s1, 4(\$s0) add \$s2, \$s2, \$s1 addi \$s0, \$s0, 8 bne \$t1, \$s0, LOOP

2.18.4 [5] <2.7> What is the total number of MIPS instructions executed?

2.18.5 [5] <2.7> Translate the loops above into C. Assume that the C-level integer *i* is held in register \$t1, \$s2 holds the C-level integer called *result*, and \$s0 holds the base address of the integer MemArray.

2.18.6 [5] <2.7> Rewrite the loop in MIPS assembly to reduce the number of MIPS instructions executed.

Exercise 2.19

For the following problems, the table holds C code functions. Assume that the first function listed in the table is called first. You will be asked to translate these C code routines into MIPS Assembly.

a.	<pre>int compare(int a, int b) { if (sub(a, b) >= 0) return 1; else return 0; } int sub (int a, int b) { return a-b; }</pre>
b.	<pre>int fib_iter(int a, int b, int n){ if(n == 0) return b; else return fib_iter(a+b, a, n-1); }</pre>

2.19.1 [15] <2.8> Implement the C code in the table in MIPS assembly. What is the total number of MIPS instructions needed to execute the function?

2.19.2 [5] <2.8> Functions can often be implemented by compilers “in-line”. An in-line function is when the body of the function is copied into the program space, allowing the overhead of the function call to be eliminated. Implement an “in-line” version of the C code in the table in MIPS assembly. What is the reduction in the total number of MIPS assembly instructions needed to complete the function? Assume that the C variable *n* is initialized to 5.

2.19.3 [5] <2.8> For each function call, show the contents of the stack after the function call is made. Assume the stack pointer is originally at addresss 0x7fffffc, and follow the register conventions as specified in Figure 2.11.

The following three problems in this exercise refer to a function *f* that calls another function *func*. The code for C function *func* is already compiled in another module using the MIPS calling convention from Figure 2.14. The function declaration for *func* is “int func(int a, int b);”. The code for function *f* is as follows:

a.	<pre>int f(int a, int b, int c){ return func(func(a,b),c); }</pre>
b.	<pre>int f(int a, int b, int c){ return func(a,b)+func(b,c); }</pre>

2.19.4 [10] <2.8> Translate function *f* into MIPS assembler, also using the MIPS calling convention from Figure 2.14. If you need to use registers \$t0 through \$t7, use the lower-numbered registers first.

2.19.5 [5] <2.8> Can we use the tail-call optimization in this function? If no, explain why not. If yes, what is the difference in the number of executed instructions in *f* with and without the optimization?

2.19.6 [5] <2.8> Right before your function `f` from Problem 2.19.4 returns, what do we know about contents of registers `$t5`, `$s3`, `$ra`, and `$sp`? Keep in mind that we know what the entire function `f` looks like, but for function `func` we only know its declaration.

Exercise 2.20

This exercise deals with recursive procedure calls. For the following problems, the table has an assembly code fragment that computes the factorial of a number. However, the entries in the table have errors, and you will be asked to fix these errors.

a.	<pre> FACT: addi \$sp, \$sp, -8 sw \$ra, 4(\$sp) sw \$a0, 0(\$sp) slti \$t0, \$a0, 1 beq \$t0, \$0, L1 addi \$v0, \$0, 1 addi \$sp, \$sp, 8 jr \$ra L1: addi \$a0, \$a0, -1 jal FACT lw \$a0, 4(\$sp) lw \$ra, 0(\$sp) addi \$sp, \$sp, 8 mul \$v0, \$a0, \$v0 jr \$ra </pre>
b.	<pre> FACT: addi \$sp, \$sp, -8 sw \$ra, 4(\$sp) sw \$a0, 0(\$sp) slti \$t0, \$a0, 1 beq \$t0, \$0, L1 addi \$v0, \$0, 1 addi \$sp, \$sp, 8 jr \$ra L1: addi \$t0, \$t0, -1 jal FACT lw \$a0, 4(\$sp) lw \$ra, 0(\$sp) addi \$sp, \$sp, 8 mul \$v0, \$a0, \$v0 jr \$ra </pre>

2.20.1 [5] <2.8> The MIPS assembly program above computes the factorial of a given input. The integer input is passed through register `$a0`, and the result is returned in register `$v0`. In the assembly code, there are a few errors. Correct the MIPS errors.

2.20.2 [10] <2.8> For the recursive factorial MIPS program above, assume that the input is 4. Rewrite the factorial program to operate in a nonrecursive manner.

Restrict your register usage to registers \$s0-\$s7. What is the total number of instructions used to execute your solution from 2.20.2 versus the recursive version of the factorial program?

2.20.3 [5] <2.8> Show the contents of the stack after each function call, assuming that the input is 4.

For the following problems, the table has an assembly code fragment that computes a Fibonacci number. However, the entries in the table have errors, and you will be asked to fix these errors.

a.	<pre> FIB: addi \$sp,\$sp, -12 sw \$ra, 0(\$sp) sw \$s1, 4(\$sp) sw \$a0, 8(\$sp) slti \$t0, \$a0, 1 beq \$t0, \$0, L1 addi \$v0,\$a0, \$0 j EXIT L1: addi \$a0,\$a0, -1 jal FIB addi \$s1,\$v0, \$0 addi \$a0,\$a0, -1 jal FIB add \$v0, \$v0, \$s1 EXIT: lw \$ra, 0(\$sp) lw \$a0, 8(\$sp) lw \$s1, 4(\$sp) addi \$sp, \$sp, 12 jr \$ra </pre>
b.	<pre> FIB: addi \$sp,\$sp, -12 sw \$ra, 0(\$sp) sw \$s1, 4(\$sp) sw \$a0, 8(\$sp) slti \$t0, \$a0, 1 beq \$t0, \$0, L1 addi \$v0,\$a0, \$0 j EXIT L1: addi \$a0,\$a0, -1 jal FIB addi \$s1,\$v0, \$0 addi \$a0,\$a0, -1 jal FIB add \$v0, \$v0, \$s1 EXIT: lw \$ra, 0(\$sp) lw \$a0, 8(\$sp) lw \$s1, 4(\$sp) addi \$sp, \$sp, 12 jr \$ra </pre>

2.20.4 [5] <2.8> The MIPS assembly program above computes the Fibonacci of a given input. The integer input is passed through register \$a0, and the result is returned in register \$v0. In the assembly code, there are a few errors. Correct the MIPS errors.

2.20.5 [10] <2.8> For the recursive Fibonacci MIPS program above, assume that the input is 4. Rewrite the Fibonacci program to operate in a nonrecursive manner. Restrict your register usage to registers \$s0-\$s7. What is the total number of instructions used to execute your solution from 2.20.2 versus the recursive version of the factorial program?

2.20.6 [5] <2.8> Show the contents of the stack after each function call, assuming that the input is 4.

Exercise 2.21

Assume that the stack and the static data segments are empty and that the stack and global pointers start at address 0x7fff fffc and 0x1000 8000, respectively. Assume the calling conventions as specified in Figure 2.11 and that function inputs are passed using registers \$a0 and returned in register \$v0. Assume that leaf functions may only use saved registers.

a.	<pre>main() { leaf_function(1); } int leaf_function (int f) { int result; result = f + 1; if (f > 5) return result; leaf_function(result); }</pre>
b.	<pre>int my_global = 100; main() { int x = 10; int y = 20; int z; z = my_function(x, my_global) } int my_function(int x, int y) { return x - y; }</pre>

2.21.1 [5] <2.8> Show the contents of the stack and the static data segments after each function call.

2.21.2 [5] <2.8> Write MIPS code for the code in the table above.

2.21.3 [5] <2.8> If the leaf function could use temporary registers (\$t0, \$t1, etc.), write the MIPS code for the code in the table above.

The following three problems in this exercise refer to this function, written in MIPS assembler following the calling conventions from Figure 2.14:

a.	<pre>f: sub \$s0,\$a0,\$a3 sll \$v0,\$s0,0x1 add \$v0,\$a2,\$v0 sub \$v0,\$v0,\$a1 jr \$ra</pre>
b.	<pre>f: addi \$sp,\$sp,8 sw \$ra,4(\$sp) sw \$s0,0(\$sp) move \$s0,\$a2 jal g add \$v0,\$v0,\$s0 lw \$ra,4(\$sp) lw \$s0,0(\$sp) addi \$sp,\$sp,-8 jr \$ra</pre>

2.21.4 [10] <2.8> This code contains a mistake that violates the MIPS calling convention. What is this mistake and how should it be fixed?

2.21.5 [10] <2.8> What is the C equivalent of this code? Assume that the function's arguments are named a, b, c, etc. in the C version of the function.

2.21.6 [10] <2.8> At the point where this function is called register \$a0, \$a1, \$a2, and \$a3 have values 1, 100, 1000, and 30, respectively. What is the value returned by this function? If another function g is called from f, assume that the value returned from g is always 500.

Exercise 2.22

This exercise explores ASCII and Unicode conversion. The following table shows strings of characters.

a.	A byte
b.	computer

2.22.1 [5] <2.9> Translate the strings into decimal ASCII byte values.

2.22.2 [5] <2.9> Translate the strings into 16-bit Unicode (using hex notation and the Basic Latin character set).

The following table shows hexadecimal ASCII character values.

a.	61 64 64
b.	73 68 69 66 74

2.22.3 [5] <2.5, 2.9> Translate the hexadecimal ASCII values to text.

Exercise 2.23

In this exercise, you will be asked to write a MIPS assembly program that converts strings into the number format as specified in the table.

a.	positive integer decimal strings
b.	two's complement hexadecimal integer s

2.23.1 [10] <2.9> Write a program in MIPS assembly language to convert an ASCII number string with the conditions listed in the table above, to an integer. Your program should expect register \$a0 to hold the address of a null-terminated string containing some combination of the digits 0 through 9. Your program should compute the integer value equivalent to this string of digits, then place the number in register \$v0. If a nondigit character appears anywhere in the string, your program should stop with the value -1 in register \$v0. For example, if register \$a0 points to a sequence of three bytes $50_{\text{ten}}, 52_{\text{ten}}, 0_{\text{ten}}$ (the null-terminated string “24”), then when the program stops, register \$v0 should contain the value 24_{ten} .

Exercise 2.24

Assume that the register \$t1 contains the address 0x1000 0000 and the register \$t2 contains the address 0x1000 0010.

a.	lb \$t0, 0(\$t1) sw \$t0, 0(\$t2)
b.	lb \$t0, 0(\$t1) sb \$t0, 0(\$t2)

2.24.1 [5] <2.9> Assume that the data (in hexadecimal) at address 0x1000 0000 is:

1000 0000	12	34	56	78
-----------	----	----	----	----

What value is stored at the address pointed to by register \$t2? Assume that the memory location pointed to \$t2 is initialized to 0xFFFF FFFF.

2.24.2 [5] <2.9> Assume that the data (in hexadecimal) at address 0x1000 0000 is:

1000 0000	80	80	80	80
-----------	----	----	----	----

What value is stored at the address pointed to by register \$t2? Assume that the memory location pointed to \$t2 is initialized to 0x0000 0000.

2.24.3 [5] <2.9> Assume that the data (in hexadecimal) at address 0x1000 0000 is:

1000 0000	11	00	00	FF
-----------	----	----	----	----

What value is stored at the address pointed to by register \$t2? Assume that the memory location pointed to \$t2 is initialized to 0x5555 5555.

Exercise 2.25

In this exercise, you will explore 32-bit constants in MIPS. For the following problems, you will be using the binary data in the table below.

a.	1010 1101 0001 0000 0000 0000 0000 0010 _{two}
b.	1111 1111 1111 1111 1111 1111 1111 1111 _{two}

2.25.1 [10] <2.10> Write the MIPS code that creates the 32-bit constants listed above and stores that value to register \$t1

2.25.2 [5] <2.6, 2.10> If the current value of the PC is 0x00000000, can you use a single jump instruction to get to the PC address as shown in the table above?

2.25.3 [5] <2.6, 2.10> If the current value of the PC is 0x00000600, can you use a single branch instruction to get to the PC address as shown in the table above?

2.25.4 [5] <2.6, 2.10> If the current value of the PC is 0x00400600, can you use a single branch instruction to get to the PC address as shown in the table above?

2.25.5 [10] <2.10> If the immediate field of a MIPS instruction was only 8 bits wide, write the MIPS code that creates the 32-bit constants listed above and stores that value to register \$t1. Do not use the lui instruction.

For the following problems, you will be using the MIPS assembly code as listed in the table.

a.	lui \$t0, 0x1234 ori \$t0, \$t0, 0x5678
b.	ori \$t0, \$t0, 0x5678 lui \$t0, 0x1234

2.25.6 [5] <2.6, 2.10> What is the value of register \$t0 after the sequence of code in the table above?

2.25.7 [5] <2.6, 2.10> Write C code that is equivalent to the assembly code in the table. Assume that the largest constant that you can load into a 32-bit integer is 16 bits.

Exercise 2.26

For this exercise, you will explore the range of branch and jump instructions in MIPS. For the following problems, use the hexadecimal data in the table below.

a.	0x00001000
b.	0xFFFFC0000

2.26.1 [10] <2.6, 2.10> If the PC is at address 0x00000000, how many branch (no jump instructions) do you need to get to the address in the table above?

2.26.2 [10] <2.6, 2.10> If the PC is at address 0x00000000, how many jump instructions (no jump register instructions or branch instructions) are required to get to the target address in the table above?

2.26.3 [10] <2.6, 2.10> In order to reduce the size of MIPS programs, MIPS designers have decided to cut the immediate field of I-type instructions from 16 bits to 8 bits. If the PC is at address 0x00000000, how many branch instructions are needed to set the PC to the address in the table above?

For the following problems, you will be using making modifications to the MIPS instruction set architecture.

a.	8 registers
b.	10 bit immediate/address field

2.26.4 [10] <2.6, 2.10> If the instruction set of the MIPS processor is modified, the instruction format must also be changed. For each of the suggested changes above, what is the impact on the range of addresses in a beq instruction? Assume that all instructions remain 32 bits long and any changes made to the instruction

format of I-type instructions only increase/decrease the immediate field of the beq instruction.

2.26.5 [10] <2.6, 2.10> If the instruction set of the MIPS processor is modified, the instruction format must also be changed. For each of the suggested changes above, what is the impact on the range of addresses a jump instruction? Assume that instructions remain 32 bits long and any changes made to the instruction format of J-type instructions only impact the address field of the jump instruction.

2.26.6 [10] <2.6, 2.10> If the instruction set of the MIPS processor is modified, the instruction format must also be changed. For each of the suggested changes above, what is the impact on the range of addresses a jump register instruction, assuming that each instruction must be 32 bits.

Exercise 2.27

In the following problems, you will be using exploring different addressing modes in the MIPS instruction set architecture. These different addressing modes are listed in the table below.

a.	Register Addressing
b.	PC-relative Addressing

2.27.1 [5] <2.10> In the table above are different addressing modes of the MIPS instruction set. Give an example MIPS instructions that shows the MIPS addressing mode.

2.27.2 [5] <2.10> For the instructions in 2.27.1, what is the instruction format type used for the given instruction?

2.27.3 [5] <2.10> List benefits and drawbacks of a particular MIPS addressing mode. Write MIPS code that shows these benefits and drawbacks.

In the following problems, you will be using the MIPS assembly code as listed below to explore the tradeoffs of the immediate field in the MIPS I-type instructions.

a.	0x00000000 0x00000004	lui \$s0, 100 ori \$s0, \$s0, 40
b.	0x00000100 0x00000104	addi \$t0, \$0, 0x0000 lw \$t1, 0x4000(\$t0)

2.27.4 [15] <2.10> For the MIPS statements above, show the bit-level instruction representation of each of the instructions in hexadecimal.

2.27.5 [10] <2.10> By reducing the size of the immediate fields of the I-type and J-type instructions, we can save on the number of bits needed to represent instructions. If the immediate field of I-type instructions were 8 bits and the immediate field of J-type instructions were 18 bits, rewrite the MIPS code above to reflect this change. Avoid using the `lui` instruction.

2.27.6 [5] <2.10> How many extra instructions are needed to execute your code in 2.27.5 MIPS statements in the table versus the code shown in the table above?

Exercise 2.28

The following table contains MIPS assembly code for a lock.

```
try:    MOV      R3,R4
        MOV      R6,R7
        LL       R2,0(R2)
        LL       R5,0(R1)
        SC       R3,0(R1)
        SC       R6,0(R1)
        BEQZ   R3,try
        MOV      R4,R2
        MOV      R7,R5
```

2.28.1 [5] <2.11> For each test and fail of the store conditional, how many instructions need to be executed?

2.28.2 [5] <2.11> For the load locked/store conditional code above, explain why this code may fail.

2.28.3 [15] <2.11> Rewrite the code above so that the code may operate correctly. Be sure to avoid any race conditions.

Each entry in the following table has code and also shows the contents of various registers. The notation, “`($s1)`” shows the contents of a memory location pointed to by register `$s1`. The assembly code in each table is executed in the cycle shown on parallel processors with a shared memory space.

a.

Processor 1	Processor 2	Cycle	Processor 1		MEM (\$s1)	Processor 2	
			\$t1	\$t0		\$t1	\$t0
		0	1	2	99	30	40
ll \$t1, 0(\$s1)	ll \$t1, 0(\$s1)	1					
sc \$t0, 0(\$s1)		2					
	sc \$t0, 0(\$s1)	3					

b.

Processor 1	Processor 2	Cycle	Processor 1			MEM (\$s1)	Processor 2		
			\$s4	\$t1	\$t0		\$s4	\$t1	\$t0
		0	2	3	4	99	10	20	30
	try: add \$t0, \$0, \$s4	1							
try: add \$t0, \$0, \$s4	ll \$t1, 0(\$s1)	2							
ll \$t1, 0(\$s1)		3							
sc \$t0, 0(\$s1)		4							
beqz \$t0, try	sc \$t0, 0(\$s1)	5							
add \$s4, \$0, \$t1	beqz \$t0, try	6							

2.28.4 [5] <2.11> Fill out the table with the value of the registers for each given cycle.

Exercise 2.29

The first three problems in this exercise refer to a critical section of the form

```
lock(lk);
operation
unlock(lk);
```

where the “operation” updates the shared variable `shvar` using the local (nonshared) variable `x` as follows:

	Operation
a.	<code>shvar=shvar+x;</code>
b.	<code>shvar=min(shvar,x);</code>

2.29.1 [10] <2.11> Write the MIPS assembler code for this critical section, assuming that the address of the `lk` variable is in `$a0`, the address of the `shvar` variable is in `$a1`, and the value of variable `x` is in `$a2`. Your critical section should not contain any function calls, i.e., you should include the MIPS instructions for `lock()`, `unlock()`, `max()`, and `min()` operations. Use `ll/sc` instructions to implement the `lock()` operation, and the `unlock()` operation is simply an ordinary store instruction.

2.29.2 [10] <2.11> Repeat problem 2.29.1, but this time use `ll/sc` to perform an atomic update of the `shvar` variable directly, without using `lock()` and `unlock()`. Note that in this problem there is no variable `lk`.

2.29.3 [10] <2.11> Compare the best-case performance of your code from 2.29.1 and 2.29.2, assuming that each instruction takes one cycle to execute. Note: best-case means that `ll/sc` always succeeds, the lock is always free when we want to `lock()`, and if there is a branch we take the path that completes the operation with fewer executed instructions.

2.29.4 [10] <2.11> Using your code from 2.29.2 as an example, explain what happens when two processors begin to execute this critical section at the same time, assuming that each processor executes exactly one instruction per cycle.

2.29.5 [10] <2.11> Explain why in your code from 2.29.2 register `$a1` contains the address of variable `shvar` and not the value of that variable, and why register `$a2` contains the value of variable `x` and not its address.

2.29.6 [10] <2.11> If we want to atomically perform the same operation on two shared variables (e.g., `shvar1` and `shvar2`) in the same critical section, we can do this easily using the approach from 2.29.1 (simply put both updates between the lock operation and the corresponding unlock operation). Explain why we cannot do this using the approach from 2.29.2., i.e., why we cannot use `ll/sc` to access both shared variables in a way that guarantees that both updates are executed together as a single atomic operation.

Exercise 2.30

Assembler pseudoinstructions are not a part of the MIPS instruction set, but often appear in MIPS programs. The table below contains some MIPS pseudoinstructions that ,when assembled, are translated to other MIPS assembly instructions.

a.	<code>move \$t1, \$t2</code>
b.	<code>beq \$t1, small, LOOP</code>

2.30.1 [5] <2.12> For each pseudo instruction in the table above, produce a minimal sequence of actual MIPS instructions to accomplish the same thing. You may need to use temporary registers in some cases. In the table `large` refers to a number that requires 32 bits to represent and `small` to a number that can fit into 16 bits.

The table below contains some MIPS pseudoinstructions, that when assembled, are translated to other MIPS assembly instructions.

a.	<code>la \$s0, v</code>
b.	<code>blt \$a0, \$v0, Loop</code>

2.30.2 [5] <2.12> Does the instruction in the table above need to be edited during the link phase? Why?

Exercise 2.31

The table below contains the link-level details of two different procedures. In this exercise, you will be taking the place of the linker.

a.	Procedure A				Procedure B			
Text Segment	Address	Instruction			Text Segment	Address	Instruction	
	0	lw \$a0, 0(\$gp)				0	sw \$a1, 0(\$gp)	
	4	jal 0				4	jal 0	
	
Data Segment	0	(X)			Data Segment	0	(Y)	
	
Relocation Info	Address	Instruction Type	Dependency		Relocation Info	Address	Instruction Type	Dependency
	0	lw	X			0	sw	Y
	4	jai	B			4	jal	A
Symbol Table	Address	Symbol			Symbol Table	Address	Symbol	
	-	X				-	Y	
	-	B				-	A	

b.	Procedure A				Procedure B			
Text Segment	Address	Instruction			Text Segment	Address	Instruction	
	0	lui \$at, 0				0	sw \$a0, 0(\$gp)	
	4	ori \$a0, \$at, 0				4	jmp 0	
	8	jal 0				
				0x180	jr \$ra	
Data Segment	0	(X)			Data Segment	0	(Y)	
	
Relocation Info	Address	Instruction Type	Dependency		Relocation Info	Address	Instruction Type	Dependency
	0	lui	X			0	sw	Y
	4	ori	X			4	jmp	F00
	8	jal	B			
Symbol Table	Address	Symbol			Symbol Table	Address	Symbol	
	-	X				-	Y	
	-	B				0x180	F00	

2.31.1 [5] <2.12> Link the object files above to form the executable file header. Assume that Procedure A has a text size of 0x140, data size of 0x40 and Procedure B has a text size of 0x300 and data size of 0x50. Also assume the memory allocation strategy as shown in Figure 2.13.

2.31.2 [5] <2.12> What limitations, if any, are there on the size of an executable?

2.31.3 [5] <2.12> Given your understanding of the limitations of branch and jump instructions, why might an assembler have problems directly implementing branch and jump instructions in an object file?

Exercise 2.32

The first three problems in this exercise assume that function swap, instead of the code in Figure 2.24, is defined in C as follows:

a. <pre>void swap(int v[], int k, int j){ int temp; temp=v[k]; v[k]=v[j]; v[j]=temp; }</pre>	b. <pre>void swap(int *p){ int temp; temp=*p; *p=*(p+1); *(p+1)=temp; }</pre>
--	---

2.32.1 [10] <2.13> Translate this function into MIPS assembler code.

2.32.2 [5] <2.13> What needs to change in the sort function?

2.32.3 [5] <2.13> If we were sorting 8-bit bytes, not 32-bit words, how would your MIPS code for swap in 2.32.1 change?

For the remaining three problems in this exercise, we assume that the sort function from Figure 2.27 is changed in the following way:

a. Use s-register s instead of t-register t. b. Use the bltz (branch on less than zero) instruction instead of slt and bne at the for2tst label.

2.32.4 [5] <2.13> Does this change affect the code for saving and restoring registers in Figure 2.27?

2.32.5 [10] <2.13> When sorting a 10-element array that was already sorted, how many more (or fewer) instructions are executed as a result of this change?

2.32.6 [10] <2.13> When sorting a 10-element array that was sorted in descending order (opposite of the order that `sort()` creates), how many more (or fewer) instructions are executed as a result of this change?

Exercise 2.33

The problems in this exercise refer to the following function, given as array code:

a.	<pre>int find(int a[], int n, int x){ int i; for(i=0;i!=n;i++) if(a[i]==x) return i; return -1; }</pre>
b.	<pre>int count(int a[], int n, int x){ int res=0; int i; for(i=0;i!=n;i++) if(a[i]==x) res=res+1; return res; }</pre>

2.33.1 [10] <2.14> Translate this function into MIPS assembly.

2.33.2 [10] <2.14> Convert this function into pointer-based code (in C).

2.33.3 [10] <2.14> Translate your pointer-based C code from 2.33.2 into MIPS assembly.

2.33.4 [5] <2.14> Compare the worst-case number of executed instructions per nonlast loop iteration in your array-based code from 2.33.1 and your pointer-based code from 2.33.3. Note: the worst-case occurs when branch conditions are such that the longest path through the code is taken, i.e., if there is an if statement, the result of the condition check is such that the path with more instructions is taken. However, if the result of the condition check would cause the loop to exit, then we assume that the path that keeps us in the loop is taken.

2.33.5 [5] <2.14> Compare the number of temporary registers (t-registers) needed for your array-based code from 2.33.1 and for your pointer-based code from 2.33.3.

2.33.6 [5] <2.14> What would change in your answer from 2.33.4 if registers \$t0-\$t7 and \$a0-\$a3 in the MIPS calling convention were all callee-saved, just like \$s0-\$s7?

Exercise 2.34

The table below contains ARM assembly code. In the following problems, you will translate ARM assembly code to MIPS.

a.	MOV r0, #10 LOOP: ADD r0, r1 SUBS r0, 1 BNE r0, LOOP	; init loop counter to 10 ; add r1 to r0 ; decrement counter ; if Z=0 repeat loop
b.	ROR r1, r2, #4	; r1 = r2 _{3:0} concatenated with r2 _{31:4}

2.34.1 [5] <2.16> For the table above, translate this ARM assembly code to MIPS assembly code. Assume that ARM registers r0, r1, and r2 hold the same values as MIPS registers \$s0, \$s1, and \$s2, respectively. Use MIPS temporary registers (\$t0, etc.) where necessary.

2.34.2 [5] <2.16> For the ARM assembly instructions in the table above, show the bit fields that represent the ARM instructions.

The table below contains MIPS assembly code. In the following problems, you will translate MIPS assembly code to ARM.

a.	slt \$t0, \$s0, \$s1 blt \$t0, \$0, FARAWAY
b.	add \$s0, \$s1, \$s2

2.34.3 [5] <2.16> For the table above, find the ARM assembly code that corresponds to the sequence of MIPS assembly code.

2.34.4 [5] <2.16> Show the bit fields that represent the ARM assembly code.

Exercise 2.35

The ARM processor has a few different addressing modes that are not supported in MIPS. The following problems explore these new addressing modes.

a.	LDR r0, [r1]	; r0 = memory[r1]
b.	LDMIA r0, {r1, r2, r4}	; r1 = memory[r0], r2 = memory[r0+4] ; r4 = memory[r0+8]

2.35.1 [5] <2.16> Identify the type of addressing mode of the ARM assembly instructions in the table above.

2.35.2 [5] <2.16> For the ARM assembly instructions above, write a sequence of MIPS assembly instructions to accomplish the same data transfer.

In the following problems, you will compare code written using the ARM and MIPS instruction sets. The following table shows code written in the ARM instruction set.

a.	LDR r0, =Table1 LDR r1, #100 EOR r2, r2, r2 ADDLP: LDR r4, [r0] ADD r2, r2, r4 ADD r0, r0, #4 SUBS r1, r1, #1 BNE ADDLP	;load base address of table ;initialize loop counter ;clear r2 ;get first addition operand ;add to r2 ;increment to next table element ;decrement loop counter ;if loop counter != 0, go to ADDLP
b.	ROR r1, r2, #4	;r1 = r2 _{3:0} concatenated with r2 _{31:4}

2.35.3 [10] <2.16> For the ARM assembly code above, write an equivalent MIPS assembly code routine.

2.35.4 [5] <2.16> What is the total number of ARM assembly instructions required to execute the code? What is the total number of MIPS assembly instructions required to execute the code?

2.35.5 [5] <2.16> Assuming that the average CPI of the MIPS assembly routine is the same as the average CPI of the ARM assembly routine, and the MIPS processor has an operation frequency that is 1.5 times the ARM processor, how much faster is the ARM processor than the MIPS processor?

Exercise 2.36

The ARM processor has an interesting way of supporting immediate constants. This exercise investigates those differences. The following table contains ARM instructions.

a.	ADD, r3, r2, r1, LSL #3 ;r3 = r2 + (r1 << 3)
b.	ADD, r3, r2, r1, ROR #3 ;r3 = r2 + (r1, rotated_right 3 bits)

2.36.1 [5] <2.16> Write the equivalent MIPS code for the ARM assembly code above.

2.36.2 [5] <2.16> If the register R1 had the constant value of 8, rewrite your MIPS code to minimize the number of MIPS assembly instructions needed.

2.36.3 [5] <2.16> If the register R1 had the constant value of 0x06000000, rewrite your MIPS code to minimize the number of MIPS assembly instructions needed.

The following table contains MIPS instructions.

a.	addi r3, r2, 0x1
b.	addi r3, r2, 0x8000

2.36.4 [5] <2.16> For the MIPS assembly code above, write the equivalent ARM assembly code.

Exercise 2.37

This exercise explores the differences between the MIPS and x86 instruction sets. The following table contains x86 assembly code.

a.	mov edx, [esi+4*ebx]
b.	<pre>START: mov ax, 00101100b mov cx, 00000011b mov bx, 11110000b and ax, bx or ax, cx</pre>

2.37.1 [10] <2.17> Write pseudo code for the given routine.

2.37.2 [10] <2.17> What is the equivalent MIPS for the given routine?

The following table contains x86 assembly instructions.

a.	mov edx, [esi+4*ebx]
b.	add eax, 0x12345678

2.37.3 [5] <2.17> For each assembly instruction, show the size of each of the bit fields that represent the instruction. Treat the label MY_FUNCTION as a 32-bit constant.

2.37.4 [10] <2.17> Write equivalent MIPS assembly statements.

Exercise 2.38

The x86 instruction set includes the REP prefix that causes the instruction to be repeated a given number of times or until a condition is satisfied. The first three problems in this exercise refer to the following x86 instruction:

	Instruction	Interpretation
a.	REP MOVSB	Repeat until ECX is zero: Mem8[EDI]=Mem8[ESI], EDI=EDI+1, ESI=ESI+1, ECX=ECX-1
b.	REP MOVS D	Repeat until ECX is zero: Mem32[EDI]=Mem32[ESI], EDI=EDI+4, ESI=ESI+4, ECX=ECX-1

2.38.1 [5] <2.17> What would be a typical use for this instruction?

2.38.2 [5] <2.17> Write MIPS code that performs the same operation, assuming that \$a0 corresponds to ECX, \$a1 to EDI, \$a2 to ESI, and \$a3 to EAX.

2.38.3 [5] <2.17> If the x86 instruction takes one cycle to read memory, one cycle to write memory, and one cycle for each register update, and if MIPS takes one cycle per instruction, what is the speed-up of using this x86 instruction instead of the equivalent MIPS code when ECX is very large? Assume that the clock cycle time for x86 and MIPS is the same.

The remaining three problems in this exercise refer to the following function, given in both C and x86 assembly. For each x86 instruction, we also show its length in the x86 variable-length instruction format and the interpretation (what the instruction does). Note that the x86 architecture has very few registers compared to MIPS, and as a result the x86 calling convention is to push all arguments onto the stack. The return value of an x86 function is passed back to the caller in the EAX register.

	C code	x86 code
a.	int f(int a, int b){ return a+b; }	f: push %ebp ; 1B, push %ebp to stack mov %esp,%ebp ; 2B, move %esp to %ebp mov 0xc(%ebp),%eax ; 3B, load 2 nd arg to %eax add 0x8(%ebp),%eax ; 3B, add 1 st arg to %eax pop %ebp ; 1B, restore %ebp ret ; 1B, return
b.	void f(int *a, int *b){ *a=*a+*b; *b=*a; }	f: push %ebp ; 1B, push %ebp to stack mov %esp,%ebp ; 2B, move %esp to %ebp mov 8(%ebp),%eax ; 3B, load 1 st arg into %eax mov 12(%ebp),%ecx ; 3B, load 2 nd arg into %ecx mov (%eax),%edx ; 2B, load *a into %edx add (%ecx),%edx ; 2B, add *b to %edx mov %edx,(%eax) ; 2B, store %edx to *a mov %edx,(%ecx) ; 2B, store %edx to *b pop %ebp ; 1B, restore %ebp ret ; 1B, return

2.38.4 [5] <2.17> Translate this function into MIPS assembly. Compare the size (how many bytes of instruction memory are needed) for this x86 code and for your MIPS code.

2.38.5 [5] <2.17> If the processor can execute two instructions per cycle, it must at least be able to read two consecutive instructions in each cycle. Explain how it would be done in MIPS and how it would be done in x86.

2.38.6 [5] <2.17> If each MIPS instruction takes one cycle, and if each x86 instruction takes one cycle plus a cycle for each memory read or write it has to perform, what is the speed-up of using x86 instead of MIPS? Assume that the clock cycle time is the same in both x86 and MIPS, and that the execution takes the shortest possible path through the function (i.e., every loop is exited immediately and every if statement takes the direction that leads toward the return from the function). Note that x86 ret instruction reads the return address from the stack.

Exercise 2.39

The CPI of the different instruction types is given in the following table.

	Arithmetic	Load/Store	Branch
a.	2	10	3
b.	1	10	4

2.39.1 [5] <2.18> Assume the following instruction breakdown given for executing a given program:

	Instructions (in millions)
Arithmetic	500
Load/Store	300
Branch	100

What is the execution time for the processor if the operation frequency is 5 GHz?

2.39.2 [5] <2.18> Suppose that new, more powerful arithmetic instructions are added to the instruction set. On average, through the use of these more powerful arithmetic instructions, we can reduce the number of arithmetic instructions needed to execute a program by 25%, and the cost of increasing the clock cycle time by only 10%. Is this a good design choice? Why?

2.39.3 [5] <2.18> Suppose that we find a way to double the performance of arithmetic instructions? What is the overall speed-up of our machine? What if we find a way to improve the performance of arithmetic instructions by 10 times!?

The following table shows the proportions of instruction execution for the different instruction types.

	Arithmetic	Load/Store	Branch
a.	60%	20%	20%
b.	80%	15%	5%

2.39.4 [5] <2.18> Given the instruction mix above and the assumption that an arithmetic instruction requires 2 cycles, a load/store instruction takes 6 cycles, and a branch instruction takes 3 cycles, find the average CPI.

2.39.5 [5] <2.18> For a 25% improvement in performance, how many cycles, on average, may an arithmetic instruction take if load/store and branch instructions are not improved at all?

2.39.6 [5] <2.18> For a 50% improvement in performance, how many cycles, on average, may an arithmetic instruction take if load/store and branch instructions are not improved at all?

Exercise 2.40

The first three problems in this exercise refer to the following function, given in MIPS assembly. Unfortunately, the programmer of this function has fallen prey to the pitfall of assuming that MIPS is a word-addressed machine, but in fact MIPS is byte addressed.

a.	<pre> ; int f(int a[], int n, int x); f: move \$v0,\$zero ; ret=0 move \$t0,\$zero ; i=0 L: add \$t1,\$t0,\$a0 ; &(a[i]) lw \$t1,0(\$t1) ; read a[i] bne \$t1,\$a2,S ; if(a[i]==x) addi \$v0,\$v0,1 ; ret++; S: addi \$t0,\$t0,1 ; i++; bne \$t0,\$a1,L ; repeat if i!=n jr \$ra ; return ret </pre>
-----------	--

b.

```

: void f(int *a, int *b, int n);
f: move $t0,$a0      ; p=a
    move $t1,$a1      ; q=b
    add  $t2,$a2,$a0   ; &(a[n])
L:  lw   $t3,0($t0)   ; read *p
    lw   $t4,0($t1)   ; read *q
    add $t3,$t3,$t4   ; *p+*q
    sw   $t3,0($t0)   ; *p=*p+*q
    addi $t0,$t0,1     ; p=p+1
    addi $t1,$t1,1     ; q=q+1
    bne $t0,$t2,L      ; repeat if p!=&(a[n])
    jr  $ra             ; return

```

Note that in MIPS assembly the “;” character denotes that the remainder of the line is a comment.

2.40.1 [5] <2.18> The MIPS architecture requires word-sized accesses (lw and sw) to be word-aligned, i.e. the lowermost 2 bits of the address must both be zero. If an address is not word-aligned, the processor raises a “bus error” exception. Explain how this alignment requirement affects the execution of this function.

2.40.2 [5] <2.18> If “a” was a pointer to the beginning of an array of one-byte elements, and if we replaced lw and sw with lb (load byte) and sb (store byte), respectively, would this function be correct? Note: lb reads a byte from memory, sign-extends it, and places it into the destination register, while sb stores the least-significant byte of the register into memory.

2.40.3 [5] <2.18> Change this code to make it correct for 32-bit integers.

The remaining three problems in this exercise refer to a program that allocates memory for an array, fills the array with some numbers, calls the sort function from Figure 2.27, and then prints out the array. The main function of the program is as follows (given as both C and MIPS code):

main code in C	MIPS version of the main code
<pre> main(){ int *v; int n=5; v=my_alloc(5); my_init(v,n); sort(v,n); . . . } </pre>	<pre> main: li \$s0,5 move \$a0,\$s0 jal my_alloc move \$s1,\$v0 move \$a0,\$s1 move \$a1,\$s0 jal my_init move \$a0,\$s1 move \$a1,\$s0 jal sort </pre>

The `my_alloc` function is defined as follows (given as both C and MIPS code). Note that the programmer of this function has fallen prey to the pitfall of using a pointer to an automatic variable `arr` outside the function in which it is defined.

my_alloc in C	MIPS code for my_alloc
<pre>int *my_alloc(int n){ int arr[n]; return arr; }</pre>	<pre>my_alloc: addu \$sp,\$sp,-4 ; Push sw \$fp,0(\$sp) ; \$fp to stack move \$fp,\$sp ; Save \$sp in \$fp sll \$t0,\$a0,2 ; We need 4*n bytes sub \$sp,\$sp,\$t0 ; Make room for arr move \$v0,\$sp ; Return address of arr move \$sp,\$fp ; Restore \$sp from \$fp lw \$fp,0(sp) ; Pop \$fp addiu \$sp,\$sp,4 ; from stack jr ra</pre>

The `my_init` function is defined as follows (MIPS code):

a.	<pre>my_init: move \$t0,\$zero ; i=0 move \$t1,\$a0 L: sw \$zero,0(\$t1) ; v[i]=0 addiu \$t1,\$t1,4 addiu \$t0,\$t0,1 ; i=i+1 bne \$t0,\$a1,L ; until i==n jr \$ra</pre>
b.	<pre>my_init: move \$t0,\$zero ; i=0 move \$t1,\$a0 L: sub \$t2,\$a1,\$t0 sw \$t2,0(\$t1) ; a[i]=n-i addiu \$t1,\$t1,4 addiu \$t0,\$t0,1 ; i=i+1; bne \$t0,\$a1,L ; until i==n jr \$ra</pre>

2.40.4 [5] <2.18> What are the contents (values of all five elements) of array `v` right before the “`jal sort`” instruction in the main code is executed?

2.40.5 [15] <2.18, 2.13> What are the contents of array `v` right before the `sort` function enters its outer loop for the first time? Assume that registers `$sp`, `$s0`, `$s1`, `$s2`, and `$s3` have values of `0x1000`, `20`, `40`, `7`, and `1`, respectively, at the beginning of the main code (right before “`li $s0, 5`” is executed).

2.40.6 [10] <2.18, 2.13> What are the contents of the 5-element array pointed by `v` right after “`jal sort`” returns to the main code?

**Answers to
Check Yourself**

§2.2, page 80: MIPS, C, Java

§2.3, page 87: 2) Very slow

§2.4, page 93: 3) -8_{ten}

§2.5, page 101: 4) `sub $s2, $s0, $s1`

§2.6, page 104: Both. AND with a mask pattern of 1s will leave 0s everywhere but the desired field. Shifting left by the right amount removes the bits from the left of the field. Shifting right by the appropriate amount puts the field into the rightmost bits of the word, with 0s in the rest of the word. Note that AND leaves the field where it was originally, and the shift pair moves the field into the rightmost part of the word.

§2.7, page 111: I. All are true. II. 1).

§2.8, page 122: Both are true.

§2.9, page 127: I. 2) II. 3)

§2.10, page 136: I. 4) $+-128K$. II. 6) a block of 256M. III. 4) `sll`

§2.11, page 139: Both are true.

§2.12, page 148: 4) Machine independence.



这本最畅销的计算机组成书籍经过全面更新，关注现今发生在计算机体系结构领域的革命性变革：从单处理器发展到多核微处理器，从串行发展到并行。与前几版一样，本书采用了MIPS处理器来展示计算机硬件技术、汇编语言、计算机算术、流水线、存储器层次结构以及I/O等基本功能。此外，本书还包括一些关于ARM和x86体系结构的介绍。

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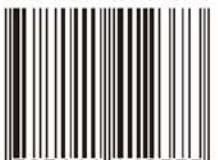
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