Irv Englander

4th Edition

The Architecture of COMPUTER HARDWARE, SYSTEMS SOFTWARE & NETWORKING

An Information Technology Approach

International Student Version

FOURTH EDITION

THE ARCHITECTURE OF COMPUTER HARDWARE, SYSTEM SOFTWARE, AND NETWORKING

AN INFORMATION TECHNOLOGY APPROACH

INTERNATIONAL STUDENT VERSION

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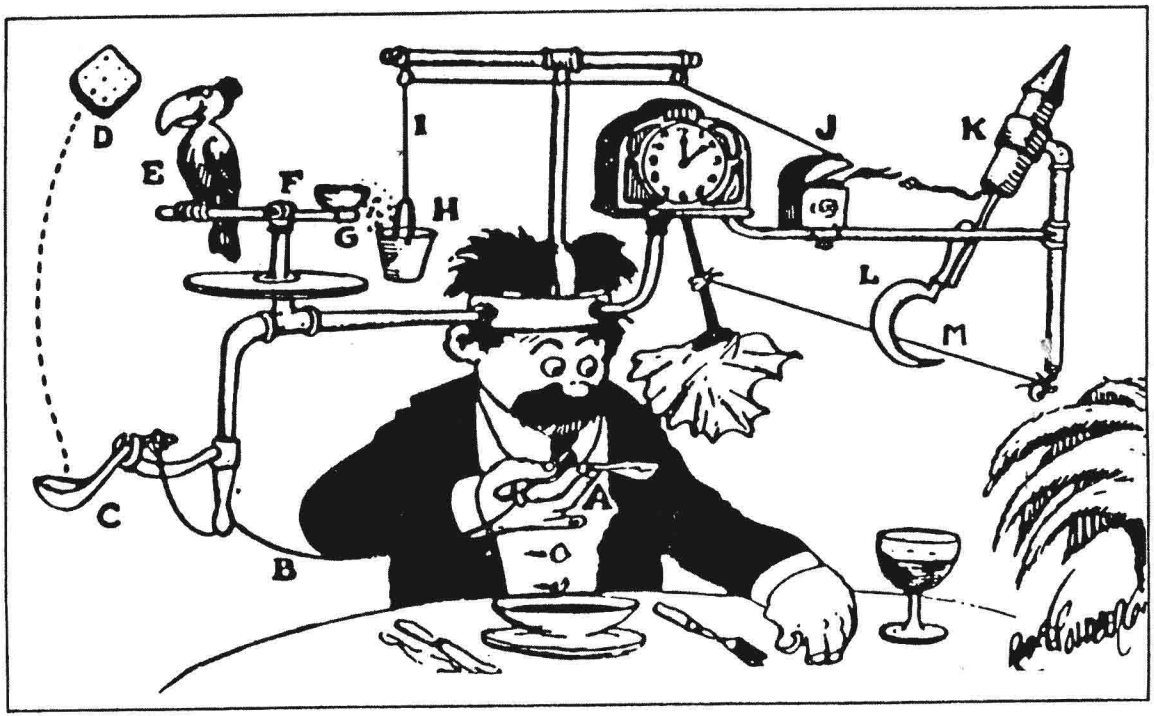
The Self-Operating Napkin

The professo walks in his sleep, strolls through a cactus field in his bare feet, and screams out an idea for self-operating napkin.

As you rise spoon of soup (A) to your mouth it pulls string (B), thereby jerking ladle (C) which throws cracker (D) past parrot (E). Parrot jumps after cracker and perch (F) tilts, upsetting seeds (G) into pail (H). Extra weight in pail pulls cord (I) which opens and lights automatic cigar lighter (J), setting off sky-rocket (K) which causes sickle (L) to cut string (M) and allow pendulum with attached napkin to swing back and forth thereby wiping off your chin.

After the meal, substitute harmonica for the napkin and you'll be able to entertain the guests with a little music.



PREFACE

The modern world offers lots of readily available online resources for learning. Wikipedia, Google, news sources, millions of Web sites and blogs, even YouTube, offer access to information in nearly any subject that triggers your curiosity and interest. Nonetheless, I continue to believe that for deep understanding of something, nothing beats the integrated approach and focus of an old-fashioned printed-on-paper textbook.

When I open a new book, in *any* subject, the first thing I want to know is what the book has to offer that makes it worth my while to read it. I would like to try to help you answer that question for the book that you're holding in your hand.

The information systems and technology fields are wonderfully exciting places to be! It seems as though every day brings new developments that alter the ways we create and work with information. Of course, with this excitement comes a challenge. To be a successful player in IS or IT we have to be adaptable and flexible.

Much of the change occurs around computer system technology. The computer is, after all, at the foundation of information systems. A deep understanding of computer systems is, therefore, an essential element of success. We must be able to understand each new development, assess its value, and place it in the context of our knowledge of computer systems.

The subject of this book is the architecture of computer systems. Computer architecture is about the structure and operation of digital computers. Computer architecture is concerned with the operational methods of the hardware; with the services provided by operating system software; with the acquisition, processing, storage, and output of data; and with the interaction between computers.

There is a tendency for people in information systems and technology to neglect a study of computer architecture. After all, the technology changes so rapidly—is it really worth trying to understand something that may be out of date by the time I finish this book? There is no question that computer technology has evolved rapidly. The computer in a personal computer, or even in a cell phone or MP3 player is far more powerful than the mainframe computer of twenty-five years ago, with memory, disk and flash storage capacity, display and multimedia capability, and ease of use that would have been unthinkable just a few years ago. Even more important, connecting systems to work together is now routine and simple.

Interestingly enough, however, as profound as advances in the technology have been, the concepts of computer architecture that really matter have changed only nominally over the last sixty years. The new technologies are based on a foundation of architectural concepts that were developed many years ago. The architecture of a modern computer system was developed in the 1940s. The instruction set in a modern personal computer

is nearly identical to that of computers built in the 1950s and 1960s. Modern operating system techniques were developed in the 1960s. The graphical user interface is based on a 1960s project. The Internet is built from concepts developed more than forty years ago.

So you see that an understanding of computer architecture makes it possible to "ride the wave" of technological change, secure in the feeling that you are equipped to deal with new developments as they occur, and to have fun doing so. When you are done reading this book you will have substantial knowledge about how a computer works and a good understanding of the operating concepts, the hardware, and system software that make up a computer. You will see the interaction between computers and between data and the computer. Plus, you will have learned lots of jargon that you can show off at parties and job interviews.

This textbook is designed for a wide range of readers, both undergraduate and graduate. The material is specifically directed toward IS and IT majors. There are no explicit prerequisites, although the book assumes that the student is familiar with a personal computer. It also assumes (but does not require) some basic programming skills: although there is no programming in the book, program code is occasionally used as an example to clarify an idea, and a knowledge of programming is helpful at understanding instruction set design and program execution concepts. The material in this textbook conforms to the criteria of the IT Infrastructure course as described in the December 2008 draft of the joint IS 2008 standard curriculum. Although the material in this book may be useful as background for system design and implementation project courses, the course can be placed anywhere in the curriculum.

Most instructors will not cover the entire textbook in a single semester. The organization of the book is designed to allow an instructor to cover the major topic areas in different levels of depth, depending on the experience and needs of the students. On the other hand, it is my intention that this book will serve a student as a useful reference long after the formal course is completed. It is designed for use as a book where a professional can look up the basic concepts that clarify new developments as they occur.

This text is the outgrowth of courses that I have taught to IS majors and minors at Bentley University at both the undergraduate and graduate level for thirty years. Student responses to the material and the approach have generally been very enthusiastic. Many students have returned after graduation to tell me that their knowledge in this area has directly contributed to their career development. Along the way, student comments have also been extremely helpful to me in the book's continuing evolution.

Those familiar with previous editions will notice that the organization of the fourth edition has undergone substantial revision to reflect current technological practices and trends. In particular, it is no longer reasonable to discuss computers as individual units without also considering the networks that tie them together; computer networking is now covered thoroughly in its own section, and there is an increased emphasis on the integration and synergy of the various components of the computer system and on the system as a whole. Still, the basic philosophy, organization, and approach remain essentially similar to those of the first edition, reflecting the unchanging nature of the underlying principles.

ORGANIZATION OF THE FOURTH EDITION OF THE BOOK

The biggest challenge for me as the author of this book has been to preserve the guiding principles established in the first edition, while reflecting the major changes in the way computers are used, in the rapid deployment of new technology, and in the resulting evolution of IS/IT curriculum to reflect those changes. The fourth edition is the most substantial revision of this book to date, with a new title, a new chapter on systems, and significantly increased coverage of networking. The case study chapters have been updated and moved to the Web, along with the chapter on programming tools and the supplementary chapters on logic design and instruction addressing. Still, users of previous editions will find much that is familiar; after all, the way in which computers are used in IS/IT may have changed, but the basic guiding principles of computer architecture are essentially the same as they have been for many years.

The book is now organized into five parts totaling eighteen chapters, plus four additional supplementary chapters that are posted on the Web. The first part serves as an introduction and overview of the role of the computer in information systems; it introduces the concept of a system and provides a brief introduction to each of the components that make up a modern computer system. Each of the remaining four parts deals with a single architectural aspect of the computer system.

Part Two discusses the role and representation of data in the computer. Here we consider numbers, text, sound, images, video, and other data forms. Part Three presents the hardware architecture and operational concepts. It introduces the components of a computer and shows how they collaborate to execute computer instructions, discusses the nature of a computer instruction set, and explores the interaction between the CPU, memory, and I/O peripheral devices. Part Four presents a thorough introduction to the basics of computer networking. Part Five discusses the system software, the programs that function to make the resources of the computer system, and other interconnected computer systems and components, accessible to the user and to application programs.

The approach within each group of chapters is layered. Each new layer builds upon the previous material to add depth and understanding to the reader's knowledge. Each topic section consists of a short introduction that places the topic to be discussed into the context of the computer system as a whole and then lays out in detail the organization of the chapters within the section. Each topic area is introduced as gently as possible, using ideas and examples that are already familiar to the student. Successive material is progressive and accumulative. In addition to the numerous examples that are used throughout the text, the supplementary chapters offer substantial case studies that show application of the text material to current examples of importance. Overall, the approach is gentle, progressive, and accumulative. As much as possible, each section is self-contained.

An overview of the organization of each part follows. More details can be found in the introductions to each section.

Part One consists of two chapters that present a short overview of computing, placing architectural concepts into the context of information technology. Chapter 1 introduces the components of a computer system and shows the relationships among the components.

It also presents a simple model of computing and discusses the importance of standards and protocols in the development of computer systems. The chapter concludes with a short history of computers from the architectural point of view. Chapter 2 focuses on the concepts of systems, models, and system architectures, using various types of computer systems as examples.

Chapters 3 through 5 comprise Part Two. Chapter 3 introduces number systems and basic number system operations; it then explores the relationships between numbers in different number bases and the conversion techniques between the different representations. Chapter 4 investigates different types of data formats, including alphanumeric, image, video, and audio formats. It considers the relationship between numerical and character-based representations and briefly introduces various devices and data formats used for data input and output. Chapter 5 studies the various formats that are used to represent and to perform calculations on integer and floating point numbers.

Part Three discusses the hardware architecture and operational aspects of the computer. Chapter 6 begins the study with the introduction of the Little Man Computer, a simple model that provides a surprisingly accurate representation of the CPU and memory. The model is used to develop the concept of an instruction set and to explain the basic principles of the von Neumann architecture. Chapter 7 extends the discussion to a real computer. It introduces the components of the CPU and shows their relationship to the Little Man Computer model. It introduces the bus concept, explains the operation of memory, presents the instruction fetch-execute cycle, and discusses the instruction set. It identifies important classes of instructions and discusses the ways in which instructions can be categorized.

Chapter 8 expands the material in Chapter 7 to consider more advanced features of the CPU and memory. It offers an overview of various CPU architectures. It continues with a discussion of techniques for improving memory access, particularly cache memory, and an introduction to current CPU organization, design, and implementation techniques, including pipelining and superscalar processing. This chapter also introduces multiprocessing (or multicore, in current terminology) concepts.

Chapter 9 presents the principles of I/O operation, and Chapter 10 illustrates how I/O is performed in various I/O devices. Chapter 11 discusses the computer system as a whole. It discusses interconnection techniques and integration of the various hardware components. It also addresses the interconnection of computers to increase computer performance and reliability, with a specific focus on clustering and on grid computing.

Three supplementary chapters on the Web provide additional resources to support the chapters in Part Three. Supplementary Chapter 1 (SC1) offers an introduction to Boolean algebra, combinatorial logic, and sequential logic for those readers that would like a deeper understanding of the computer in its simplest and most elegant form. Supplementary Chapter 2 (SC2) offers three detailed case studies of important architectures: the Intel x86 family, including the Pentium IV architecture and Itanium extensions, the PowerPC, and the IBM zSystem. Supplementary Chapter 3 (SC3) discusses alternative approaches to instruction addressing.

Part Four presents a thorough introduction to networking. Chapter 12 introduces the major features and characteristics of networking, including a careful introduction to communication channels, a detailed discussion of layered network models, with particular emphasis on TCP/IP and Ethernet models, an introduction to network topologies, and finally, a discussion of the different types of networks in use, including LANs, MANs, WANs,

and the backbones that form the foundation of the Internet. Chapter 13 expands on the material in Chapter 12 to discuss specific details of various layers, including discussions of DNS, TCP connections, IP and physical address resolution, the operation of Ethernet, alternative protocols, and more. Chapter 14 focuses primarily on communication channel technology, including analog and digital signaling, modulation and data conversion techniques between analog and digital, the characteristics of transmission media, and wireless networking. A portion of Chapter 14 appeared in previous editions as a supplementary chapter.

Part Five is dedicated to a discussion of system software. Chapter 15 provides an overview of the operating system. It explains the different roles played by the operating system and introduces the facilities and services provided. Chapter 16 presents the role of the operating system from the viewpoint of the user of a system. Chapter 17 discusses the all-important topic of file systems. Chapter 18 discusses the operating system as a resource manager, with an in-depth discussion of memory management, scheduling, process control, network services, and other basic operating system services. Chapter 18 includes a detailed introduction to virtual memory technique, and also includes an introduction to virtual machines. In addition to its hardware discussions, Supplementary Chapter 3 also provides current Windows, UNIX/Linux, and z/OS case studies.

A fourth supplementary chapter provides an introduction to the system development software that is used for the preparation and execution of programs.

A detailed list of the changes between the second and third editions of the book can be found at the book Web site, www.wiley.com/go/global/englander.

This book has been a continuing labor of love. My primary goal has been to create and maintain a textbook that explains computer architecture in a way that conveys to you, the reader, the sense of excitement and fun that I believe makes a career in information systems and technology so satisfying. I hope that I have succeeded to some extent.

ADDITIONAL RESOURCES

Additional resources for students and instructors may be found at the textbook Web site, www.wiley.com/go/global/englander. I can also be reached directly by e-mail at ienglander@bentley.edu. Although I am happy to communicate with students, I am unable to supply tutorial help or answers to review questions and exercises in the book.

ACKNOWLEDGMENTS

I've discovered that a major, ongoing textbook project is a formidable task. Many individuals have helped to make the task manageable—and kept me going when, from time to time, I became convinced that textbooks really *do* appear by magic and are *not* written by humans. It is impossible to thank people adequately for all their help and support. First and foremost, a special thank you to my nearest and dearest friends, Wilson Wong, Rich Braun, Luis Fernandez, Jan Harrington, Ray Brackett, and Evan Horn. Their continuing backup through four editions has been amazing! I couldn't have asked for a better support team. The champagne is on ice. *Yet* again!

My continuing thanks, too, to Stuart Madnick. Stuart, your technical inspiration and personal encouragement was invaluable to me when I struggled to get the first edition

of this book going. You helped me to believe that this project was actually possible and worthwhile. That support has continued to inspire me through every subsequent edition.

Next, I thank the many colleagues at Bentley University who shared their ideas, experiences, and encouragement. Colleagues Wilson Wong, David Yates, Doug Robertson, Mary Ann Robbert, Lynn Senne, Jim Linderman, Kay Green, and Peggy Beranek have all offered contributions that have substantially improved the book over four editions. A special thank you, David, for your helpful technical discussions and reviews of the new data communications material in the fourth edition, and to you, Wilson, for serving as a technical reviewer for both the third and fourth editions, providing many comments, rewrites, and suggestions for clarification, and for creating many of the ancillary materials for the book. A special thank you also to Linda Cotroneo, our Bentley CIS Department Academic Administrative Assistant, who for the past twenty years has generously offered more empathy and support than any person deserves. From the bottom of my heart, Linda, thank you!

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I would like to acknowledge the reviewers who gave of their time and effort to assure that this book was as good as it could be: Dr. Stu Westin, The University of Rhode Island; Alan Pinck, Algonquin College; Mark Jacobi, Programme Director for Undergrad Computing at Sheffield Hallam University; Dr. Dave Protheroe, South Bank University, London; Julius Ilinskas, Kaunas University of Technology; Anthony Richardson, United States Army Informations Systems Engineering Command; Renee A.Weather, Old Dominion University; Jack Claff, Southern Cross University; Jan L. Harrington, Marist College; YoungJoon Byun, California State University, Monterey Bay; William Myers, Belmont Abbey College; Barbara T. Grabowski, Benedictine College; G.E. Strouse, York College of Pennsylvania; Martin J. Doyle, Temple University; Richard Socash, Metropolitan State College of Denver; Fred Cathers, Franklin University. Your comments, suggestions, and constructive criticism have made a real difference in the quality of this book. Thank you.

Many colleagues offered corrections to previous editions that have had important impact on the quality of the current edition. To each and everyone, your assistance in eliminating errors has been much appreciated. Among these, I especially wish to acknowledge David Feinstein and his crew at the University of South Alabama, Gordon Grimsey of AIT in Auckland, New Zealand, and Stu Westin of University of Rhode Island for efforts well above and beyond the call of duty. Stu has also generously made his excellent Little Man Simulator publicly available, for which I am truly grateful. Thanks for everything, Stu.

Numerous students, too many to name you all, also offered corrections, made suggestions, and provided ideas. Please accept my deepest appreciation and thanks.

I hope that I have not forgotten anyone. If I have, I apologize.

I have strived to make this book as technically accurate as is humanly possible. Nonetheless, I know that errors have a way of creeping in when one least expects them. I would greatly appreciate hearing from readers who find errors that need correction. Your comments and suggestions about the book are also welcome.

To four outstanding teachers and great human beings:

With your guidance, inspiration, and patience, you showed me
that everything is possible.

Dr. Sidney H. Englander (1900–1980)
and Mildred K. Englander (1906–2008),
in memoriam my father and mother

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teacher of Science in Cleveland Heights, Ohio
from 1927 to 1970

Edith B. Malin, in memoriam
teacher of English in Cleveland Heights, Ohio
from 1924 to 1958

BRIEF CONTENTS

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