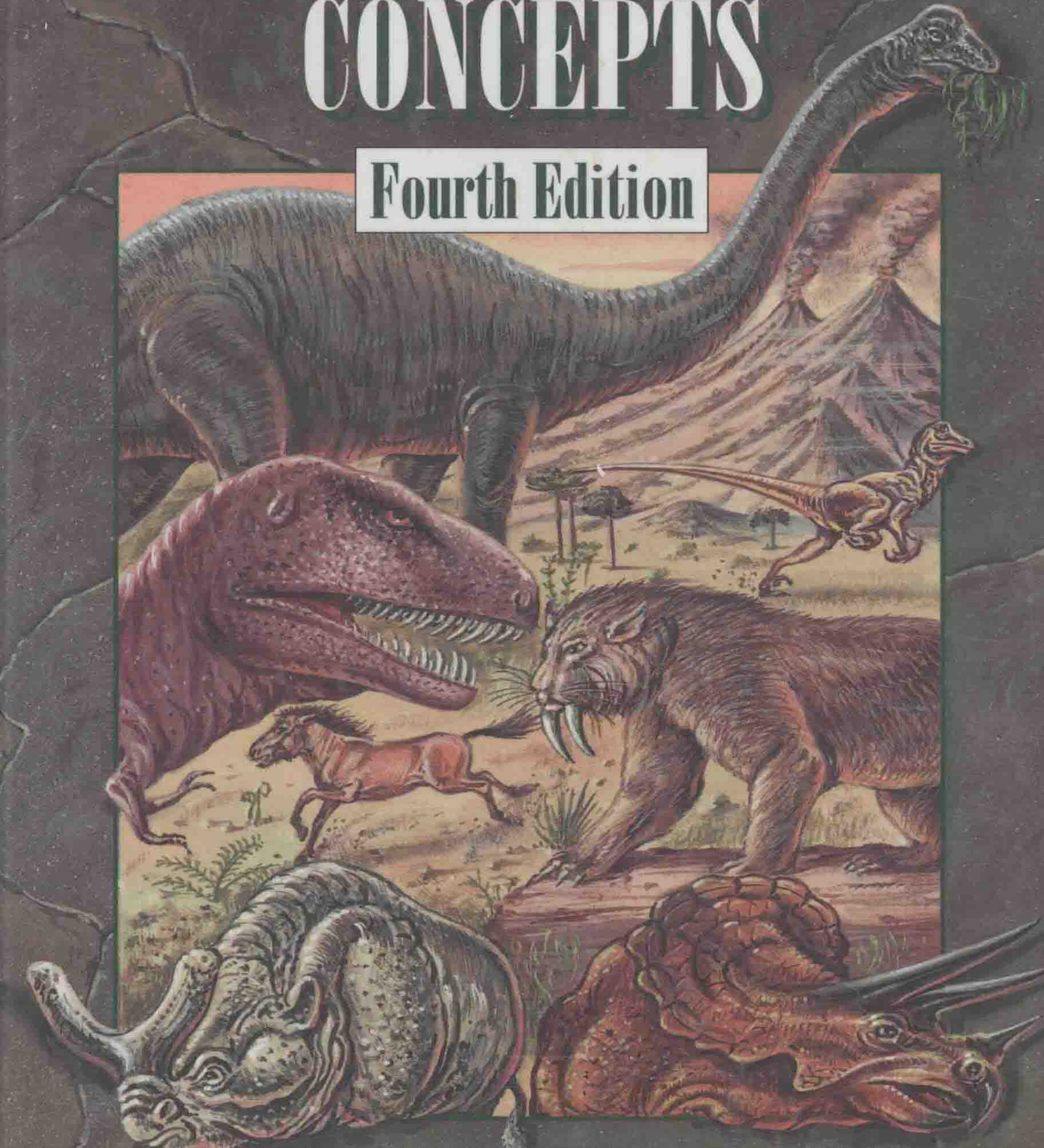
OPERATING SYSTEM CONCEPTS

Fourth Edition



SILBERSCHATZ

GALVIN

FOURTH EDITION

OPERATING SYSTEM CONCEPTS

Abraham Silberschatz
University of Texas

Peter B. Galvin
Brown University

Addison-Wesley Publishing Company
Reading, Massachusetts • Menlo Park, California • New York
Don Mills, Ontario • Wokingham, England • Amsterdam • Bonn
Sydney • Singapore • Tokyo • Madrid • San Juan • Milan • Paris

Sponsoring Editor: *Deborah Lafferty*
Senior Editor: *Tom Stone*
Senior Production Supervisor: *Helen Wythe*
Marketing Manager: *Phyllis Cerys*
Technical Art Coordinator: *Susan London-Payne*
Cover and Endpaper Designer: *Howard S. Friedman*
Manufacturing Manager: *Roy Logan*

Library of Congress Cataloging-in-Publication Data

Silberschatz, Abraham.
Operating system concepts / Abraham Silberschatz, Peter B. Galvin.
p. cm.
Includes bibliographical references and index.
ISBN 0-201-50480-4
1. Operating systems (Computers) I. Galvin, Peter B. II. Title.
QA76.76.063S5583 1994
005.4'3--dc20 93-24415
CIP

Reproduced by Addison-Wesley from camera-ready copy supplied by the authors.

Reprinted with corrections February, 1994

ISBN 0-201-50480-4
2 3 4 5 6 7 8 9 10-MA-9594

To my parents, Wira and Mietek,
my wife, Haya,
and my children, Lemor, Sivan and Aaron.

Avi Silberschatz

To Carla and Gwendolyn.

Peter Galvin

PREFACE

Operating systems are an essential part of a computer system. Similarly, a course on operating systems is an essential part of a computer-science education. This book is intended as a text for an introductory course in operating systems at the junior or senior undergraduate level, or first-year graduate level. It provides a clear description of the *concepts* that underlie operating systems.

This book does not concentrate on any particular operating system or hardware. Instead, it discusses fundamental concepts that are applicable to a variety of systems. We do, however, present a large number of examples that pertain to UNIX and other popular operating systems. In particular, we use Sun Microsystem's Solaris 2 operating system, a version of UNIX, which recently has been transformed into a modern operating system with support for threads at the kernel and user levels, symmetric multiprocessing, and real-time scheduling. Other examples used include Microsoft MS-DOS, Windows, and Windows/NT, IBM OS/2, the Apple Macintosh Operating System, and DEC VMS and TOPS-20, among others.

Prerequisites

As prerequisites, we assume that the reader is familiar with general computer organization and a high-level language, such as PASCAL. The hardware topics required for an understanding of operating systems are included in Chapter 2. We use pseudo-PASCAL notation for code examples, but the algorithms can be understood without a thorough knowledge of PASCAL.

Content of this Book

The text is organized in six major parts:

- **Overview** (Chapters 1 to 3). These chapters explain what operating systems *are,* what they *do,* and how they are *designed* and *constructed.* They explain how the concept of an operating system has developed, what the common features of an operating system are, what an operating system does for the user, and what it does for the computer-system operator. The presentation is motivational, historical, and explanatory in nature. We have avoided a discussion of how things are done internally in these chapters. Therefore, they are suitable for individuals or lower-level classes who want to learn what an operating system is, without getting into the details of the internal algorithms. Additionally, Chapter 2 covers the hardware topics which are important to an understanding of operating systems. Readers well-versed in hardware topics, including I/O, DMA, and hard disk operation, may chose to skim or skip this chapter.

- **Process management** (Chapters 4 to 7). The process concept and concurrency are at the very heart of modern operating systems. A *process* is the unit of work in a system. Such a system consists of a collection of *concurrently* executing processes, some of which are operating-system processes (those that execute system code), and the rest of which are user processes (those that execute user code). These chapters cover various methods for process scheduling, interprocess communication, process synchronization, and deadlock handling. Also included under this topic is a discussion of threads.

- **Storage management** (Chapters 8 to 12). A process must be in main memory (at least partially) during execution. To improve both the utilization of CPU and the speed of its response to its users, the computer must keep several processes in memory. There are many different memory-management schemes. These schemes reflect various approaches to memory management, and the effectiveness of the different algorithms depends on the particular situation. Since main memory is usually too small to accommodate all data and programs and cannot store data permanently, the computer system must provide secondary storage to back up main memory. Most modern computer systems use disks as the primary on-line storage medium for information (both programs and data). The file system provides the mechanism for on-line storage of and access to both data and programs residing on the disks. These chapters deal with the classic internal algorithms and structures of storage management. They provide a firm practical understanding of the algorithms used — the properties, advantages, and disadvantages.

- **Protection and security** (Chapters 13 and 14). The various processes in an operating system must be protected from one another's activities. For that purpose, mechanisms exist that can be used to ensure that the files, memory segments, CPU, and other resources can be operated on by only those processes that have gained proper authorization from the operating system. Protection is a mechanism for controlling the access of programs, processes, or users to the resources defined by a computer system. This mechanism must provide a means for specification of the controls to be imposed, together with some means of enforcement. Security protects the information stored in the system (both data and code), as well as the physical resources of the computer system, from unauthorized access, malicious destruction or alteration, and accidental introduction of inconsistency.

- **Distributed systems** (Chapters 15 to 18). A *distributed system* is a collection of processors that do not share memory or a clock. Such a system provides the user with access to the various resources the system maintains. Access to a shared resource allows computation speedup and improved data availability and reliability. Such a system also provides the user with a distributed file system, which is a file-service system whose users, servers, and storage devices are dispersed among the various sites of a distributed system. A distributed system must provide various mechanisms for process synchronization and communication, for dealing with the deadlock problem and the variety of failures that are not encountered in a centralized system.

- **Case studies** (Chapters 19 to 21). The various concepts described in this book can be drawn together by describing real operating systems. Two UNIX-based operating systems are covered in detail — Berkeley 4.3BSD and Mach. These operating systems were chosen in part because UNIX at one time was almost small enough to understand and yet was not a toy operating system. Most of its internal algorithms were selected for *simplicity,* not for speed or sophistication. UNIX is readily available to computer-science departments, so many students have access to it. Mach provides an opportunity for us to study a modern operating system that provides compatibility with 4.3BSD but has a drastically different design and implementation. Chapter 21 briefly describes some of the most influential operating systems.

- **The Nachos System** (Appendix). A good way to gain a deeper understanding of modern operating systems concepts is for the students to get their hands dirty — to take apart the code for an operating system, to see how it works at a low level, to build significant pieces of the operating system themselves, and to observe the impact of those changes. The Nachos instructional operating system, which is briefly described in the Appendix, provides the opportunity to see how the basic concepts introduced in this text can be used to solve real-world problems. The Nachos system was developed by Professor Thomas Anderson from the University of California at Berkeley, to complement the third edition of this text, and it is freely available in the public domain via the Internet. Reviewers, who have used the Nachos project at other universities, call it a practical and positive supplement.

The Fourth Edition

Many comments and suggestions were forwarded to us concerning our previous editions. These, together with our own observations, have prodded us to produce this fourth edition. Our basic procedure was to reorganize and rewrite the material in each chapter, adding new information, examples, and diagrams where appropriate. We also brought older material up to date and removed material that was no longer of interest. Finally, we improved the exercises and updated the references.

Substantive revisions were made in the following chapters:

- **Chapter 1.** We have condensed some of the material related to older systems and have expanded our discussion of parallel, distributed, and real-time systems.
- **Chapter 2.** We collected coverage of strictly-hardware topics from the other chapters and reorganized them here, making this material easier to skip if it is already understood, and easier to use as a reference. We also expanded discussion of I/O topics, caching, and protection.
- **Chapter 4.** This chapter introduces the process concept. The material in this chapter appeared in parts of old Chapters 4 and 5. We moved the IPC material from old Chapter 5 to Chapter 4, since we believe that the material should be covered as part of the discussion on the process concept rather that as part of the process coordination chapter. We also expanded our discussion on threads considerably, and included Solaris 2 threads as an example.
- **Chapter 5.** This chapter is a reorganized old Chapter 4. It now deals primarily with CPU scheduling issues.
- **Chapter 6.** This chapter is a reorganized old Chapter 5. We removed Eisenberg and McGuire's solution to the critical-section problem for *n* processes from the main text (it is now an exercise). We also condensed the discussions concerning the critical region concept. We added new material on atomic transactions, including write-ahead logging and concurrency control schemes. Synchronization in Solaris 2 is included as an example.

- **Chapters 8 and 9.** We have added new material on up-to-date computer architectures that support paging and segmentation for large address spaces. Segmentation and paging are illuminated by an OS/2 example.
- **Chapters 10, 11, and 12.** We have expanded the material and completely reorganized the presentation of the file-system concept and implementation. We now present the logical aspect of the file system in Chapter 10, the implementation issues in Chapter 11, and the underlying secondary storage system in Chapter 12. We also have added new material on swap space, stable storage, recovery, reliability and performance.
- **Chapters 13 and 14.** We have separated old Chapter 11 into two chapters — one dealing with protection issues (Chapter 13), the other dealing with security issues (Chapter 14). In each of these chapters, we have reorganized the material, and have added new information. Major expansions include coverage of the Internet Worm and viruses.
- **Chapters 15 and 16.** We have separated old Chapter 12 into two chapters — one dealing with network structures (Chapter 15), the other dealing with distributed system structure (Chapter 16). In each of these chapters, we have reorganized the material, and have added new information. Major expansions include coverage of network protocols and functionality, remote services, thread-management, and the Open Software Foundation's Distributed Computing Environment (DCE) thread package.
- **Chapter 17.** This is old Chapter 14 on distributed file systems. We have brought the material up-to-date in this rapidly changing area.
- **Chapter 18.** This is old Chapter 13 on distributed coordination. We have brought the material up-to-date and added new sections on the two-phase commit protocol and concurrency control schemes.
- **Chapter 19.** This chapter on UNIX has been updated to reflect the current state of BSD UNIX and its current implementation.
- **Chapter 20.** This is old Chapter 16 on the Mach operating system. It has been updated to describe components of Mach version 3.
- **Appendix.** This is a new Appendix, which was was authored by Professor Thomas Anderson from UC Berkeley. This Appendix provides a brief tutorial introduction to the Nachos system. The Appendix presents the philosophy governing the Nachos environment as well as providing a general introduction to the Nachos operating system and the five project activities which accompany the software. The Appendix concludes with instructions for retrieving Nachos from the Internet via ftp.

Mailing List and Supplements

We now provide an environment where users can communicate among themselves and with us. We have created a mailing list consisting of users of our book with the e-mail address — os-book@cs.utexas.edu. If you wish to be on the list, please send a message to avi@cs.utexas.edu indicating your name, affiliation, and e-mail address.

For information about the teaching supplements, which complement this book, mail may be sent to os4e@aw.com.

Errata

We have attempted to clean up every error in this new edition, but — as happens with operating systems — there will undoubtedly still be some obscure bugs. We would appreciate it if you, the reader, would notify us of any errors or omissions in the book. Also, if you would like to suggest improvements or to contribute exercises, we would be glad to hear from you. Any correspondence should be sent to A. Silberschatz, Department of Computer Sciences, The University of Texas.

Acknowledgments

This book is derived from the previous editions, all of which were coauthored by James Peterson. Other people that have helped with the previous editions include Randy Bentson, Jeff Brumfield, Gael Buckley, Thomas Casavant, Ajoy Kumar Datta, Joe Deck, Robert Fowler, G. Scott Graham, Rebecca Hartman, Wayne Hathaway, Christopher Haynes, Richard Kieburtz, Carol Kroll, Thomas LeBlanc, John Leggett, Michael Molloy, Ed Posnak, John Quarterman, Charles Oualline, John Stankovic, Steven Stepanek, Louis Stevens, and John Werth.

Lyn Dupré copyedited the book; Cliff Wilkes provided technical copyediting; Sara Strandtman edited our text into troff format. Debbie Lafferty, Tom Stone, and Helen Wythe were helpful with book production.

Chapter 17 was derived from a paper by Levy and Silberschatz [1990]. Chapter 19 was derived from a paper by Quarterman et al. [1985]. John Quarterman helped us to convert the material on UNIX 4.2BSD to UNIX 4.3BSD. David Black worked extensively with us to update Chapter 20.

We thank the following people, who reviewed this edition of the book: Joseph Boykin, P. C. Capon, John Carpenter, Thomas Doeppner, Caleb Drake, Hans Flack, Mark Holliday, Jerrold Leichter, Ted Leung, Gary Lippman, Carolyn Miller, Yoichi Muraoka, Jim M. Ng, Boris Putanec, Adam Stauffer, Hal Stern, David Umbaugh, Steve Vinoski, and J. S. Weston.

A.S.
P.B.G.

CONTENTS

PART ONE

OVERVIEW

An *operating system* is a program that acts as an intermediary between a user of a computer and the computer hardware. The purpose of an operating system is to provide an environment in which a user can execute programs in a *convenient* and *efficient* manner.

We trace the development of operating systems from the first hands-on systems to current multiprogrammed and time-shared systems. Understanding the reasons behind the development of operating systems gives us an appreciation for what an operating system does and how it does it.

The operating system must ensure the correct operation of the computer system. To prevent user programs from interfering with the proper operation of the system, the hardware must provide appropriate mechanisms to ensure such proper behavior. We describe the basic computer architecture that makes it possible to write a correct operating system.

The operating system provides certain services to programs and to the users of those programs in order to make the programming task easier. The specific services provided will, of course, differ from one operating system to another, but there are some common classes of services that we identify and explore.