

OPERATING SYSTEM CONCEPTS

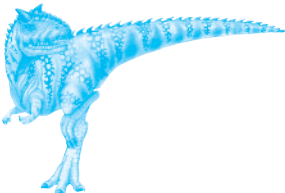
Abraham Silberschatz
Peter Baer Galvin
Greg Gagne

Ninth Edition



OPERATING SYSTEM CONCEPTS

NINTH EDITION



OPERATING SYSTEM CONCEPTS

ABRAHAM SILBERSCHATZ

Yale University

PETER BAER GALVIN

Pluribus Networks

GREG GAGNE

Westminster College



NINTH EDITION



WILEY

Vice President and Executive Publisher
Executive Editor
Editorial Assistant
Executive Marketing Manager
Senior Production Editor
Cover and title page illustrations
Cover Designer
Text Designer

Don Fowley
Beth Lang Golub
Katherine Willis
Christopher Ruel
Ken Santor
Susan Cyr
Madelyn Lesure
Judy Allan

This book was set in Palatino by the author using LaTeX and printed and bound by Courier-Kendallville. The cover was printed by Courier.

Copyright © 2013, 2012, 2008 John Wiley & Sons, Inc. All rights reserved.

No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning or otherwise, except as permitted under Sections 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc. 222 Rosewood Drive, Danvers, MA 01923, (978)750-8400, fax (978)750-4470. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030 (201)748-6011, fax (201)748-6008, E-Mail: PERMREQ@WILEY.COM.

Evaluation copies are provided to qualified academics and professionals for review purposes only, for use in their courses during the next academic year. These copies are licensed and may not be sold or transferred to a third party. Upon completion of the review period, please return the evaluation copy to Wiley. Return instructions and a free-of-charge return shipping label are available at www.wiley.com/go/evalreturn. Outside of the United States, please contact your local representative.

Founded in 1807, John Wiley & Sons, Inc. has been a valued source of knowledge and understanding for more than 200 years, helping people around the world meet their needs and fulfill their aspirations. Our company is built on a foundation of principles that include responsibility to the communities we serve and where we live and work. In 2008, we launched a Corporate Citizenship Initiative, a global effort to address the environmental, social, economic, and ethical challenges we face in our business. Among the issues we are addressing are carbon impact, paper specifications and procurement, ethical conduct within our business and among our vendors, and community and charitable support. For more information, please visit our website: www.wiley.com/go/citizenship.

ISBN: 978-1-118-06333-0

ISBN BRV: 978-1-118-12938-8

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

*To my children, Lemor, Sivan, and Aaron
and my Nicolette*

Avi Silberschatz

*To Brendan and Ellen,
and Barbara, Anne and Harold, and Walter and Rebecca*

Peter Baer Galvin

*To my Mom and Dad,
Greg Gagne*

Preface

Operating systems are an essential part of any computer system. Similarly, a course on operating systems is an essential part of any computer science education. This field is undergoing rapid change, as computers are now prevalent in virtually every arena of day-to-day life—from embedded devices in automobiles through the most sophisticated planning tools for governments and multinational firms. Yet the fundamental concepts remain fairly clear, and it is on these that we base this book.

We wrote this book as a text for an introductory course in operating systems at the junior or senior undergraduate level or at the first-year graduate level. We hope that practitioners will also find it useful. It provides a clear description of the *concepts* that underlie operating systems. As prerequisites, we assume that the reader is familiar with basic data structures, computer organization, and a high-level language, such as C or Java. The hardware topics required for an understanding of operating systems are covered in Chapter 1. In that chapter, we also include an overview of the fundamental data structures that are prevalent in most operating systems. For code examples, we use predominantly C, with some Java, but the reader can still understand the algorithms without a thorough knowledge of these languages.

Concepts are presented using intuitive descriptions. Important theoretical results are covered, but formal proofs are largely omitted. The bibliographical notes at the end of each chapter contain pointers to research papers in which results were first presented and proved, as well as references to recent material for further reading. In place of proofs, figures and examples are used to suggest why we should expect the result in question to be true.

The fundamental concepts and algorithms covered in the book are often based on those used in both commercial and open-source operating systems. Our aim is to present these concepts and algorithms in a general setting that is not tied to one particular operating system. However, we present a large number of examples that pertain to the most popular and the most innovative operating systems, including Linux, Microsoft Windows, Apple Mac OS X, and Solaris. We also include examples of both Android and iOS, currently the two dominant mobile operating systems.

The organization of the text reflects our many years of teaching courses on operating systems, as well as curriculum guidelines published by the IEEE

Computing Society and the Association for Computing Machinery (ACM). Consideration was also given to the feedback provided by the reviewers of the text, along with the many comments and suggestions we received from readers of our previous editions and from our current and former students.

Content of This Book

The text is organized in eight major parts:

- **Overview.** Chapters 1 and 2 explain what operating systems are, what they do, and how they are designed and constructed. These chapters discuss what the common features of an operating system are and what an operating system does for the user. We include coverage of both traditional PC and server operating systems, as well as operating systems for mobile devices. The presentation is motivational and explanatory in nature. We have avoided a discussion of how things are done internally in these chapters. Therefore, they are suitable for individual readers or for students in lower-level classes who want to learn what an operating system is without getting into the details of the internal algorithms.
- **Process management.** Chapters 3 through 7 describe the process concept and concurrency as the 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 methods for process scheduling, interprocess communication, process synchronization, and deadlock handling. Also included is a discussion of threads, as well as an examination of issues related to multicore systems and parallel programming.
- **Memory management.** Chapters 8 and 9 deal with the management of main memory during the execution of a process. To improve both the utilization of the 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, reflecting various approaches to memory management, and the effectiveness of a particular algorithm depends on the situation.
- **Storage management.** Chapters 10 through 13 describe how mass storage, the file system, and I/O are handled in a modern computer system. The file system provides the mechanism for on-line storage of and access to both data and programs. We describe the classic internal algorithms and structures of storage management and provide a firm practical understanding of the algorithms used—their properties, advantages, and disadvantages. Since the I/O devices that attach to a computer vary widely, the operating system needs to provide a wide range of functionality to applications to allow them to control all aspects of these devices. We discuss system I/O in depth, including I/O system design, interfaces, and internal system structures and functions. In many ways, I/O devices are the slowest major components of the computer. Because they represent a

performance bottleneck, we also examine performance issues associated with I/O devices.

- **Protection and security.** Chapters 14 and 15 discuss the mechanisms necessary for the protection and security of computer systems. The processes in an operating system must be protected from one another's activities, and to provide such protection, we must ensure that only processes that have gained proper authorization from the operating system can operate on the files, memory, CPU, and other resources of the system. Protection is a mechanism for controlling the access of programs, processes, or users to computer-system resources. This mechanism must provide a means of specifying the controls to be imposed, as well as a means of enforcement. Security protects the integrity of the information stored in the system (both data and code), as well as the physical resources of the system, from unauthorized access, malicious destruction or alteration, and accidental introduction of inconsistency.
- **Advanced topics.** Chapters 16 and 17 discuss virtual machines and distributed systems. Chapter 16 is a new chapter that provides an overview of virtual machines and their relationship to contemporary operating systems. Included is an overview of the hardware and software techniques that make virtualization possible. Chapter 17 condenses and updates the three chapters on distributed computing from the previous edition. This change is meant to make it easier for instructors to cover the material in the limited time available during a semester and for students to gain an understanding of the core ideas of distributed computing more quickly.
- **Case studies.** Chapters 18 and 19 in the text, along with Appendices A and B (which are available on (<http://www.os-book.com>), present detailed case studies of real operating systems, including Linux, Windows 7, FreeBSD, and Mach. Coverage of both Linux and Windows 7 are presented throughout this text; however, the case studies provide much more detail. It is especially interesting to compare and contrast the design of these two very different systems. Chapter 20 briefly describes a few other influential operating systems.

The Ninth Edition

As we wrote this Ninth Edition of *Operating System Concepts*, we were guided by the recent growth in three fundamental areas that affect operating systems:

1. Multicore systems
2. Mobile computing
3. Virtualization

To emphasize these topics, we have integrated relevant coverage throughout this new edition—and, in the case of virtualization, have written an entirely new chapter. Additionally, we have rewritten material in almost every chapter by bringing older material up to date and removing material that is no longer interesting or relevant.

We have also made substantial organizational changes. For example, we have eliminated the chapter on real-time systems and instead have integrated appropriate coverage of these systems throughout the text. We have reordered the chapters on storage management and have moved up the presentation of process synchronization so that it appears before process scheduling. Most of these organizational changes are based on our experiences while teaching courses on operating systems.

Below, we provide a brief outline of the major changes to the various chapters:

- **Chapter 1, Introduction**, includes updated coverage of multiprocessor and multicore systems, as well as a new section on kernel data structures. Additionally, the coverage of computing environments now includes mobile systems and cloud computing. We also have incorporated an overview of real-time systems.
- **Chapter 2, Operating-System Structures**, provides new coverage of user interfaces for mobile devices, including discussions of iOS and Android, and expanded coverage of Mac OS X as a type of hybrid system.
- **Chapter 3, Processes**, now includes coverage of multitasking in mobile operating systems, support for the multiprocess model in Google's Chrome web browser, and zombie and orphan processes in UNIX.
- **Chapter 4, Threads**, supplies expanded coverage of parallelism and Amdahl's law. It also provides a new section on implicit threading, including OpenMP and Apple's Grand Central Dispatch.
- **Chapter 5, Process Synchronization** (previously Chapter 6), adds a new section on mutex locks as well as coverage of synchronization using OpenMP, as well as functional languages.
- **Chapter 6, CPU Scheduling** (previously Chapter 5), contains new coverage of the Linux CFS scheduler and Windows user-mode scheduling. Coverage of real-time scheduling algorithms has also been integrated into this chapter.
- **Chapter 7, Deadlocks**, has no major changes.
- **Chapter 8, Main Memory**, includes new coverage of swapping on mobile systems and Intel 32- and 64-bit architectures. A new section discusses ARM architecture.
- **Chapter 9, Virtual Memory**, updates kernel memory management to include the Linux SLUB and SLOB memory allocators.
- **Chapter 10, Mass-Storage Structure** (previously Chapter 12), adds coverage of solid-state disks.
- **Chapter 11, File-System Interface** (previously Chapter 10), is updated with information about current technologies.
- **Chapter 12, File-System Implementation** (previously Chapter 11), is updated with coverage of current technologies.
- **Chapter 13, I/O**, updates technologies and performance numbers, expands coverage of synchronous/asynchronous and blocking/nonblocking I/O, and adds a section on vectored I/O.

- **Chapter 14, Protection**, has no major changes.
- **Chapter 15, Security**, has a revised cryptography section with modern notation and an improved explanation of various encryption methods and their uses. The chapter also includes new coverage of Windows 7 security.
- **Chapter 16, Virtual Machines**, is a new chapter that provides an overview of virtualization and how it relates to contemporary operating systems.
- **Chapter 17, Distributed Systems**, is a new chapter that combines and updates a selection of materials from previous Chapters 16, 17, and 18.
- **Chapter 18, The Linux System** (previously Chapter 21), has been updated to cover the Linux 3.2 kernel.
- **Chapter 19, Windows 7**, is a new chapter presenting a case study of Windows 7.
- **Chapter 20, Influential Operating Systems** (previously Chapter 23), has no major changes.

Programming Environments

This book uses examples of many real-world operating systems to illustrate fundamental operating-system concepts. Particular attention is paid to Linux and Microsoft Windows, but we also refer to various versions of UNIX (including Solaris, BSD, and Mac OS X).

The text also provides several example programs written in C and Java. These programs are intended to run in the following programming environments:

- **POSIX.** POSIX (which stands for *Portable Operating System Interface*) represents a set of standards implemented primarily for UNIX-based operating systems. Although Windows systems can also run certain POSIX programs, our coverage of POSIX focuses on UNIX and Linux systems. POSIX-compliant systems must implement the POSIX core standard (POSIX.1); Linux, Solaris, and Mac OS X are examples of POSIX-compliant systems. POSIX also defines several extensions to the standards, including real-time extensions (POSIX1.b) and an extension for a threads library (POSIX1.c, better known as Pthreads). We provide several programming examples written in C illustrating the POSIX base API, as well as Pthreads and the extensions for real-time programming. These example programs were tested on Linux 2.6 and 3.2 systems, Mac OS X 10.7, and Solaris 10 using the gcc 4.0 compiler.
- **Java.** Java is a widely used programming language with a rich API and built-in language support for thread creation and management. Java programs run on any operating system supporting a Java virtual machine (or JVM). We illustrate various operating-system and networking concepts with Java programs tested using the Java 1.6 JVM.
- **Windows systems.** The primary programming environment for Windows systems is the Windows API, which provides a comprehensive set of functions for managing processes, threads, memory, and peripheral devices. We supply several C programs illustrating the use of this API. Programs were tested on systems running Windows XP and Windows 7.

We have chosen these three programming environments because we believe that they best represent the two most popular operating-system models—Windows and UNIX/Linux—along with the widely used Java environment. Most programming examples are written in C, and we expect readers to be comfortable with this language. Readers familiar with both the C and Java languages should easily understand most programs provided in this text.

In some instances—such as thread creation—we illustrate a specific concept using all three programming environments, allowing the reader to contrast the three different libraries as they address the same task. In other situations, we may use just one of the APIs to demonstrate a concept. For example, we illustrate shared memory using just the POSIX API; socket programming in TCP/IP is highlighted using the Java API.

Linux Virtual Machine

To help students gain a better understanding of the Linux system, we provide a Linux virtual machine, including the Linux source code, that is available for download from the the website supporting this text (<http://www.os-book.com>). This virtual machine also includes a gcc development environment with compilers and editors. Most of the programming assignments in the book can be completed on this virtual machine, with the exception of assignments that require Java or the Windows API.

We also provide three programming assignments that modify the Linux kernel through kernel modules:

1. Adding a basic kernel module to the Linux kernel.
2. Adding a kernel module that uses various kernel data structures.
3. Adding a kernel module that iterates over tasks in a running Linux system.

Over time it is our intention to add additional kernel module assignments on the supporting website.

Supporting Website

When you visit the website supporting this text at <http://www.os-book.com>, you can download the following resources:

- Linux virtual machine
- C and Java source code
- Sample syllabi
- Set of Powerpoint slides
- Set of figures and illustrations
- FreeBSD and Mach case studies

- Solutions to practice exercises
- Study guide for students
- Errata

Notes to Instructors

On the website for this text, we provide several sample syllabi that suggest various approaches for using the text in both introductory and advanced courses. As a general rule, we encourage instructors to progress sequentially through the chapters, as this strategy provides the most thorough study of operating systems. However, by using the sample syllabi, an instructor can select a different ordering of chapters (or subsections of chapters).

In this edition, we have added over sixty new written exercises and over twenty new programming problems and projects. Most of the new programming assignments involve processes, threads, process synchronization, and memory management. Some involve adding kernel modules to the Linux system which requires using either the Linux virtual machine that accompanies this text or another suitable Linux distribution.

Solutions to written exercises and programming assignments are available to instructors who have adopted this text for their operating-system class. To obtain these restricted supplements, contact your local John Wiley & Sons sales representative. You can find your Wiley representative by going to <http://www.wiley.com/college> and clicking “Who’s my rep?”

Notes to Students

We encourage you to take advantage of the practice exercises that appear at the end of each chapter. Solutions to the practice exercises are available for download from the supporting website <http://www.os-book.com>. We also encourage you to read through the study guide, which was prepared by one of our students. Finally, for students who are unfamiliar with UNIX and Linux systems, we recommend that you download and install the Linux virtual machine that we include on the supporting website. Not only will this provide you with a new computing experience, but the open-source nature of Linux will allow you to easily examine the inner details of this popular operating system.

We wish you the very best of luck in your study of operating systems.

Contacting Us

We have endeavored to eliminate typos, bugs, and the like from the text. But, as in new releases of software, bugs almost surely remain. An up-to-date errata list is accessible from the book’s website. We would be grateful if you would notify us of any errors or omissions in the book that are not on the current list of errata.

We would be glad to receive suggestions on improvements to the book. We also welcome any contributions to the book website that could be of

use to other readers, such as programming exercises, project suggestions, on-line labs and tutorials, and teaching tips. E-mail should be addressed to os-book-authors@cs.yale.edu.

Acknowledgments

This book is derived from the previous editions, the first three of which were coauthored by James Peterson. Others who helped us with previous editions include Hamid Arabnia, Rida Bazzi, Randy Bentson, David Black, Joseph Boykin, Jeff Brumfield, Gael Buckley, Roy Campbell, P. C. Capon, John Carpenter, Gil Carrick, Thomas Casavant, Bart Childs, Ajoy Kumar Datta, Joe Deck, Sudarshan K. Dhall, Thomas Doeppner, Caleb Drake, M. Racsit Eskicioğlu, Hans Flack, Robert Fowler, G. Scott Graham, Richard Guy, Max Hailperin, Rebecca Hartman, Wayne Hathaway, Christopher Haynes, Don Heller, Bruce Hillyer, Mark Holliday, Dean Hougén, Michael Huang, Ahmed Kamel, Morty Kewstel, Richard Kiebertz, Carol Kroll, Morty Kwestel, Thomas LeBlanc, John Leggett, Jerrold Leichter, Ted Leung, Gary Lippman, Carolyn Miller, Michael Molloy, Euripides Montagne, Yoichi Muraoka, Jim M. Ng, Banu Özden, Ed Posnak, Boris Putanec, Charles Qualline, John Quarterman, Mike Reiter, Gustavo Rodriguez-Rivera, Carolyn J. C. Schauble, Thomas P. Skinner, Yannis Smaragdakis, Jesse St. Laurent, John Stankovic, Adam Stauffer, Steven Stepanek, John Sterling, Hal Stern, Louis Stevens, Pete Thomas, David Umbaugh, Steve Vinoski, Tommy Wagner, Larry L. Wear, John Werth, James M. Westall, J. S. Weston, and Yang Xiang

Robert Love updated both Chapter 18 and the Linux coverage throughout the text, as well as answering many of our Android-related questions. Chapter 19 was written by Dave Probert and was derived from Chapter 22 of the Eighth Edition of *Operating System Concepts*. Jonathan Katz contributed to Chapter 15. Richard West provided input into Chapter 16. Salahuddin Khan updated Section 15.9 to provide new coverage of Windows 7 security.

Parts of Chapter 17 were derived from a paper by Levy and Silberschatz [1990]. Chapter 18 was derived from an unpublished manuscript by Stephen Tweedie. Cliff Martin helped with updating the UNIX appendix to cover FreeBSD. Some of the exercises and accompanying solutions were supplied by Arvind Krishnamurthy. Andrew DeNicola prepared the student study guide that is available on our website. Some of the the slides were prepared by Marilyn Turnamian.

Mike Shapiro, Bryan Cantrill, and Jim Mauro answered several Solaris-related questions, and Bryan Cantrill from Sun Microsystems helped with the ZFS coverage. Josh Dees and Rob Reynolds contributed coverage of Microsoft's NET. The project for POSIX message queues was contributed by John Trono of Saint Michael's College in Colchester, Vermont.

Judi Paige helped with generating figures and presentation of slides. Thomas Gagne prepared new artwork for this edition. Owen Galvin helped copy-edit Chapter 16. Mark Wogahn has made sure that the software to produce this book (\LaTeX and fonts) works properly. Ranjan Kumar Meher rewrote some of the \LaTeX software used in the production of this new text.

Our Executive Editor, Beth Lang Golub, provided expert guidance as we prepared this edition. She was assisted by Katherine Willis, who managed many details of the project smoothly. The Senior Production Editor, Ken Santor, was instrumental in handling all the production details.

The cover illustrator was Susan Cyr, and the cover designer was Madelyn Lesure. Beverly Peavler copy-edited the manuscript. The freelance proofreader was Katrina Avery; the freelance indexer was WordCo, Inc.

Abraham Silberschatz, New Haven, CT, 2012

Peter Baer Galvin, Boston, MA, 2012

Greg Gagne, Salt Lake City, UT, 2012

Contents

PART ONE ■ OVERVIEW

Chapter 1 Introduction

- 1.1 What Operating Systems Do 4
- 1.2 Computer-System Organization 7
- 1.3 Computer-System Architecture 12
- 1.4 Operating-System Structure 19
- 1.5 Operating-System Operations 21
- 1.6 Process Management 24
- 1.7 Memory Management 25
- 1.8 Storage Management 26
- 1.9 Protection and Security 30
- 1.10 Kernel Data Structures 31
- 1.11 Computing Environments 35
- 1.12 Open-Source Operating Systems 43
- 1.13 Summary 47
- Exercises 49
- Bibliographical Notes 52

Chapter 2 Operating-System Structures

- 2.1 Operating-System Services 55
- 2.2 User and Operating-System Interface 58
- 2.3 System Calls 62
- 2.4 Types of System Calls 66
- 2.5 System Programs 74
- 2.6 Operating-System Design and Implementation 75
- 2.7 Operating-System Structure 78
- 2.8 Operating-System Debugging 86
- 2.9 Operating-System Generation 91
- 2.10 System Boot 92
- 2.11 Summary 93
- Exercises 94
- Bibliographical Notes 101

PART TWO ■ PROCESS MANAGEMENT

Chapter 3 Processes

- 3.1 Process Concept 105
- 3.2 Process Scheduling 110
- 3.3 Operations on Processes 115
- 3.4 Interprocess Communication 122
- 3.5 Examples of IPC Systems 130
- 3.6 Communication in Client–Server Systems 136
- 3.7 Summary 147
- Exercises 149
- Bibliographical Notes 161

Chapter 4 Threads

- 4.1 Overview 163
- 4.2 Multicore Programming 166
- 4.3 Multithreading Models 169
- 4.4 Thread Libraries 171
- 4.5 Implicit Threading 177
- 4.6 Threading Issues 183
- 4.7 Operating-System Examples 188
- 4.8 Summary 191
- Exercises 191
- Bibliographical Notes 199

Chapter 5 Process Synchronization

- 5.1 Background 203
- 5.2 The Critical-Section Problem 206
- 5.3 Peterson's Solution 207
- 5.4 Synchronization Hardware 209
- 5.5 Mutex Locks 212
- 5.6 Semaphores 213
- 5.7 Classic Problems of Synchronization 219
- 5.8 Monitors 223
- 5.9 Synchronization Examples 232
- 5.10 Alternative Approaches 238
- 5.11 Summary 242
- Exercises 242
- Bibliographical Notes 258

Chapter 6 CPU Scheduling

- 6.1 Basic Concepts 261
- 6.2 Scheduling Criteria 265
- 6.3 Scheduling Algorithms 266
- 6.4 Thread Scheduling 277
- 6.5 Multiple-Processor Scheduling 278
- 6.6 Real-Time CPU Scheduling 283
- 6.7 Operating-System Examples 290
- 6.8 Algorithm Evaluation 300
- 6.9 Summary 304
- Exercises 305
- Bibliographical Notes 311

Chapter 7 Deadlocks

- 7.1 System Model 315
- 7.2 Deadlock Characterization 317
- 7.3 Methods for Handling Deadlocks 322
- 7.4 Deadlock Prevention 323
- 7.5 Deadlock Avoidance 327
- 7.6 Deadlock Detection 333
- 7.7 Recovery from Deadlock 337
- 7.8 Summary 339
- Exercises 339
- Bibliographical Notes 346

PART THREE ■ MEMORY MANAGEMENT

Chapter 8 Main Memory

- 8.1 Background 351
- 8.2 Swapping 358
- 8.3 Contiguous Memory Allocation 360
- 8.4 Segmentation 364
- 8.5 Paging 366
- 8.6 Structure of the Page Table 378
- 8.7 Example: Intel 32 and 64-bit Architectures 383
- 8.8 Example: ARM Architecture 388
- 8.9 Summary 389
- Exercises 390
- Bibliographical Notes 394

Chapter 9 Virtual Memory

- 9.1 Background 397
- 9.2 Demand Paging 401
- 9.3 Copy-on-Write 408
- 9.4 Page Replacement 409
- 9.5 Allocation of Frames 421
- 9.6 Thrashing 425
- 9.7 Memory-Mapped Files 430
- 9.8 Allocating Kernel Memory 436
- 9.9 Other Considerations 439
- 9.10 Operating-System Examples 445
- 9.11 Summary 448
 - Exercises 449
 - Bibliographical Notes 461

PART FOUR ■ STORAGE MANAGEMENT

Chapter 10 Mass-Storage Structure

- 10.1 Overview of Mass-Storage Structure 467
- 10.2 Disk Structure 470
- 10.3 Disk Attachment 471
- 10.4 Disk Scheduling 472
- 10.5 Disk Management 478
- 10.6 Swap-Space Management 482
- 10.7 RAID Structure 484
- 10.8 Stable-Storage Implementation 494
- 10.9 Summary 496
 - Exercises 497
 - Bibliographical Notes 501

Chapter 11 File-System Interface

- 11.1 File Concept 503
- 11.2 Access Methods 513
- 11.3 Directory and Disk Structure 515
- 11.4 File-System Mounting 526
- 11.5 File Sharing 528
- 11.6 Protection 533
- 11.7 Summary 538
 - Exercises 539
 - Bibliographical Notes 541

Chapter 12 File-System Implementation

- 12.1 File-System Structure 543
- 12.2 File-System Implementation 546
- 12.3 Directory Implementation 552
- 12.4 Allocation Methods 553
- 12.5 Free-Space Management 561
- 12.6 Efficiency and Performance 564
- 12.7 Recovery 568
- 12.8 NFS 571
- 12.9 Example: The WAFL File System 577
- 12.10 Summary 580
 - Exercises 581
 - Bibliographical Notes 585

Chapter 13 I/O Systems

- 13.1 Overview 587
- 13.2 I/O Hardware 588
- 13.3 Application I/O Interface 597
- 13.4 Kernel I/O Subsystem 604
- 13.5 Transforming I/O Requests to Hardware Operations 611
- 13.6 STREAMS 613
- 13.7 Performance 615
- 13.8 Summary 618
 - Exercises 619
 - Bibliographical Notes 621

PART FIVE ■ PROTECTION AND SECURITY

Chapter 14 Protection

- 14.1 Goals of Protection 625
- 14.2 Principles of Protection 626
- 14.3 Domain of Protection 627
- 14.4 Access Matrix 632
- 14.5 Implementation of the Access Matrix 636
- 14.6 Access Control 639
- 14.7 Revocation of Access Rights 640
- 14.8 Capability-Based Systems 641
- 14.9 Language-Based Protection 644
- 14.10 Summary 649
- Exercises 650
- Bibliographical Notes 652

Chapter 15 Security

- 15.1 The Security Problem 657
- 15.2 Program Threats 661
- 15.3 System and Network Threats 669
- 15.4 Cryptography as a Security Tool 674
- 15.5 User Authentication 685
- 15.6 Implementing Security Defenses 689
- 15.7 Firewalling to Protect Systems and Networks 696
- 15.8 Computer-Security Classifications 698
- 15.9 An Example: Windows 7 699
- 15.10 Summary 701
- Exercises 702
- Bibliographical Notes 704

PART SIX ■ ADVANCED TOPICS

Chapter 16 Virtual Machines

- 16.1 Overview 711
- 16.2 History 713
- 16.3 Benefits and Features 714
- 16.4 Building Blocks 717
- 16.5 Types of Virtual Machines and Their Implementations 721
- 16.6 Virtualization and Operating-System Components 728
- 16.7 Examples 735
- 16.8 Summary 737
- Exercises 738
- Bibliographical Notes 739

Chapter 17 Distributed Systems

- 17.1 Advantages of Distributed Systems 741
- 17.2 Types of Network-based Operating Systems 743
- 17.3 Network Structure 747
- 17.4 Communication Structure 751
- 17.5 Communication Protocols 756
- 17.6 An Example: TCP/IP 760
- 17.7 Robustness 762
- 17.8 Design Issues 764
- 17.9 Distributed File Systems 765
- 17.10 Summary 773
- Exercises 774
- Bibliographical Notes 777

PART SEVEN ■ CASE STUDIES

Chapter 18 The Linux System

- 18.1 Linux History 781
- 18.2 Design Principles 786
- 18.3 Kernel Modules 789
- 18.4 Process Management 792
- 18.5 Scheduling 795
- 18.6 Memory Management 800
- 18.7 File Systems 809
- 18.8 Input and Output 815
- 18.9 Interprocess Communication 818
- 18.10 Network Structure 819
- 18.11 Security 821
- 18.12 Summary 824
- Exercises 824
- Bibliographical Notes 826

Chapter 19 Windows 7

- 19.1 History 829
- 19.2 Design Principles 831
- 19.3 System Components 838
- 19.4 Terminal Services and Fast User Switching 862
- 19.5 File System 863
- 19.6 Networking 869
- 19.7 Programmer Interface 874
- 19.8 Summary 883
- Exercises 883
- Bibliographical Notes 885

Chapter 20 Influential Operating Systems

- 20.1 Feature Migration 887
- 20.2 Early Systems 888
- 20.3 Atlas 895
- 20.4 XDS-940 896
- 20.5 THE 897
- 20.6 RC 4000 897
- 20.7 CTSS 898
- 20.8 MULTICS 899
- 20.9 IBM OS/360 899
- 20.10 TOPS-20 901
- 20.11 CP/M and MS/DOS 901
- 20.12 Macintosh Operating System and Windows 902
- 20.13 Mach 902
- 20.14 Other Systems 904
- Exercises 904
- Bibliographical Notes 904

PART EIGHT ■ APPENDICES

Appendix A BSD UNIX

- A.1 UNIX History A1
- A.2 Design Principles A6
- A.3 Programmer Interface A8
- A.4 User Interface A15
- A.5 Process Management A18
- A.6 Memory Management A22
- A.7 File System A24
- A.8 I/O System A32
- A.9 Interprocess Communication A36
- A.10 Summary A40
- Exercises A41
- Bibliographical Notes A42

Appendix B The Mach System

B.1 History of the Mach System	B1	B.6 Memory Management	B18
B.2 Design Principles	B3	B.7 Programmer Interface	B23
B.3 System Components	B4	B.8 Summary	B24
B.4 Process Management	B7	Exercises	B25
B.5 Interprocess Communication	B13	Bibliographical Notes	B26



Part One

Overview

An **operating system** acts as an intermediary between the 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.

An operating system is software that manages the computer hardware. The hardware must provide appropriate mechanisms to ensure the correct operation of the computer system and to prevent user programs from interfering with the proper operation of the system.

Internally, operating systems vary greatly in their makeup, since they are organized along many different lines. The design of a new operating system is a major task. It is important that the goals of the system be well defined before the design begins. These goals form the basis for choices among various algorithms and strategies.

Because an operating system is large and complex, it must be created piece by piece. Each of these pieces should be a well-delineated portion of the system, with carefully defined inputs, outputs, and functions.

Introduction



An **operating system** is a program that manages a computer's hardware. It also provides a basis for application programs and acts as an intermediary between the computer user and the computer hardware. An amazing aspect of operating systems is how they vary in accomplishing these tasks. Mainframe operating systems are designed primarily to optimize utilization of hardware. Personal computer (PC) operating systems support complex games, business applications, and everything in between. Operating systems for mobile computers provide an environment in which a user can easily interface with the computer to execute programs. Thus, some operating systems are designed to be *convenient*, others to be *efficient*, and others to be some combination of the two.

Before we can explore the details of computer system operation, we need to know something about system structure. We thus discuss the basic functions of system startup, I/O, and storage early in this chapter. We also describe the basic computer architecture that makes it possible to write a functional operating system.

Because an operating system is large and complex, it must be created piece by piece. Each of these pieces should be a well-delineated portion of the system, with carefully defined inputs, outputs, and functions. In this chapter, we provide a general overview of the major components of a contemporary computer system as well as the functions provided by the operating system. Additionally, we cover several other topics to help set the stage for the remainder of this text: data structures used in operating systems, computing environments, and open-source operating systems.

CHAPTER OBJECTIVES

- To describe the basic organization of computer systems.
- To provide a grand tour of the major components of operating systems.
- To give an overview of the many types of computing environments.
- To explore several open-source operating systems.

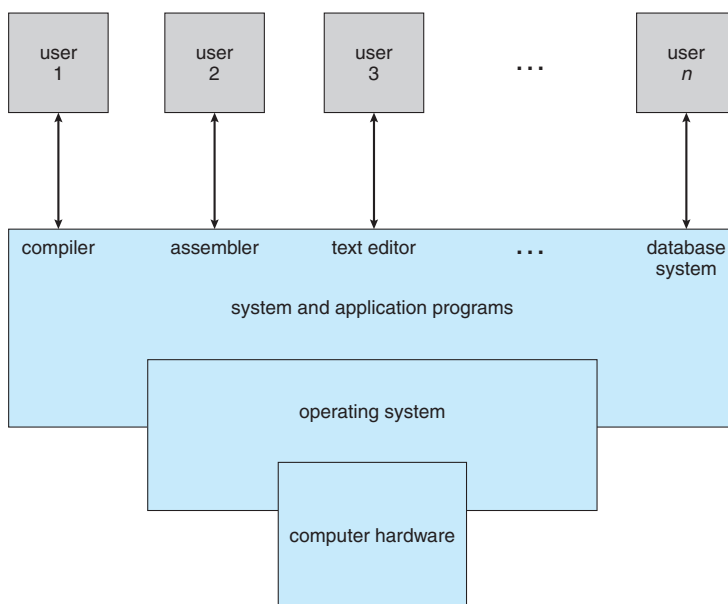


Figure 1.1 Abstract view of the components of a computer system.

1.1 What Operating Systems Do

We begin our discussion by looking at the operating system's role in the overall computer system. A computer system can be divided roughly into four components: the *hardware*, the *operating system*, the *application programs*, and the *users* (Figure 1.1).

The **hardware**—the **central processing unit (CPU)**, the **memory**, and the **input/output (I/O) devices**—provides the basic computing resources for the system. The **application programs**—such as word processors, spreadsheets, compilers, and Web browsers—define the ways in which these resources are used to solve users' computing problems. The operating system controls the hardware and coordinates its use among the various application programs for the various users.

We can also view a computer system as consisting of hardware, software, and data. The operating system provides the means for proper use of these resources in the operation of the computer system. An operating system is similar to a government. Like a government, it performs no useful function by itself. It simply provides an *environment* within which other programs can do useful work.

To understand more fully the operating system's role, we next explore operating systems from two viewpoints: that of the user and that of the system.

1.1.1 User View

The user's view of the computer varies according to the interface being used. Most computer users sit in front of a PC, consisting of a monitor, keyboard, mouse, and system unit. Such a system is designed for one user

to monopolize its resources. The goal is to maximize the work (or play) that the user is performing. In this case, the operating system is designed mostly for **ease of use**, with some attention paid to performance and none paid to **resource utilization**—how various hardware and software resources are shared. Performance is, of course, important to the user; but such systems are optimized for the single-user experience rather than the requirements of multiple users.

In other cases, a user sits at a terminal connected to a **mainframe** or a **minicomputer**. Other users are accessing the same computer through other terminals. These users share resources and may exchange information. The operating system in such cases is designed to maximize resource utilization—to assure that all available CPU time, memory, and I/O are used efficiently and that no individual user takes more than her fair share.

In still other cases, users sit at **workstations** connected to networks of other workstations and **servers**. These users have dedicated resources at their disposal, but they also share resources such as networking and servers, including file, compute, and print servers. Therefore, their operating system is designed to compromise between individual usability and resource utilization.

Recently, many varieties of mobile computers, such as smartphones and tablets, have come into fashion. Most mobile computers are standalone units for individual users. Quite often, they are connected to networks through cellular or other wireless technologies. Increasingly, these mobile devices are replacing desktop and laptop computers for people who are primarily interested in using computers for e-mail and web browsing. The user interface for mobile computers generally features a **touch screen**, where the user interacts with the system by pressing and swiping fingers across the screen rather than using a physical keyboard and mouse.

Some computers have little or no user view. For example, embedded computers in home devices and automobiles may have numeric keypads and may turn indicator lights on or off to show status, but they and their operating systems are designed primarily to run without user intervention.

1.1.2 System View

From the computer's point of view, the operating system is the program most intimately involved with the hardware. In this context, we can view an operating system as a **resource allocator**. A computer system has many resources that may be required to solve a problem: CPU time, memory space, file-storage space, I/O devices, and so on. The operating system acts as the manager of these resources. Facing numerous and possibly conflicting requests for resources, the operating system must decide how to allocate them to specific programs and users so that it can operate the computer system efficiently and fairly. As we have seen, resource allocation is especially important where many users access the same mainframe or minicomputer.

A slightly different view of an operating system emphasizes the need to control the various I/O devices and user programs. An operating system is a control program. A **control program** manages the execution of user programs to prevent errors and improper use of the computer. It is especially concerned with the operation and control of I/O devices.

1.1.3 Defining Operating Systems

By now, you can probably see that the term *operating system* covers many roles and functions. That is the case, at least in part, because of the myriad designs and uses of computers. Computers are present within toasters, cars, ships, spacecraft, homes, and businesses. They are the basis for game machines, music players, cable TV tuners, and industrial control systems. Although computers have a relatively short history, they have evolved rapidly. Computing started as an experiment to determine what could be done and quickly moved to fixed-purpose systems for military uses, such as code breaking and trajectory plotting, and governmental uses, such as census calculation. Those early computers evolved into general-purpose, multifunction mainframes, and that's when operating systems were born. In the 1960s, **Moore's Law** predicted that the number of transistors on an integrated circuit would double every eighteen months, and that prediction has held true. Computers gained in functionality and shrunk in size, leading to a vast number of uses and a vast number and variety of operating systems. (See Chapter 20 for more details on the history of operating systems.)

How, then, can we define what an operating system is? In general, we have no completely adequate definition of an operating system. Operating systems exist because they offer a reasonable way to solve the problem of creating a usable computing system. The fundamental goal of computer systems is to execute user programs and to make solving user problems easier. Computer hardware is constructed toward this goal. Since bare hardware alone is not particularly easy to use, application programs are developed. These programs require certain common operations, such as those controlling the I/O devices. The common functions of controlling and allocating resources are then brought together into one piece of software: the operating system.

In addition, we have no universally accepted definition of what is part of the operating system. A simple viewpoint is that it includes everything a vendor ships when you order “the operating system.” The features included, however, vary greatly across systems. Some systems take up less than a megabyte of space and lack even a full-screen editor, whereas others require gigabytes of space and are based entirely on graphical windowing systems. A more common definition, and the one that we usually follow, is that the operating system is the one program running at all times on the computer—usually called the **kernel**. (Along with the kernel, there are two other types of programs: **system programs**, which are associated with the operating system but are not necessarily part of the kernel, and application programs, which include all programs not associated with the operation of the system.)

The matter of what constitutes an operating system became increasingly important as personal computers became more widespread and operating systems grew increasingly sophisticated. In 1998, the United States Department of Justice filed suit against Microsoft, in essence claiming that Microsoft included too much functionality in its operating systems and thus prevented application vendors from competing. (For example, a Web browser was an integral part of the operating systems.) As a result, Microsoft was found guilty of using its operating-system monopoly to limit competition.

Today, however, if we look at operating systems for mobile devices, we see that once again the number of features constituting the operating system