



OPERATING SYSTEM CONCEPTS

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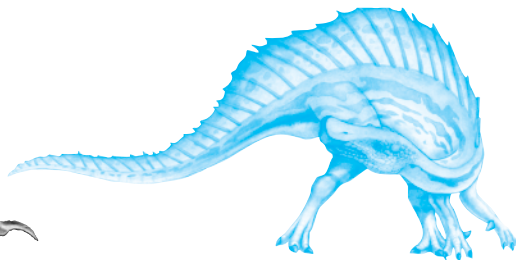
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Preface

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.



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.

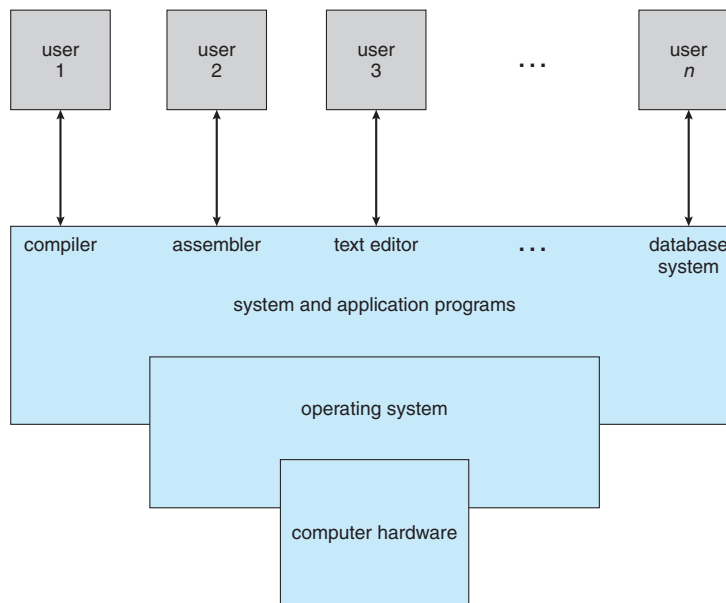


Figure 1.1 Abstract view of the components of a computer system.

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