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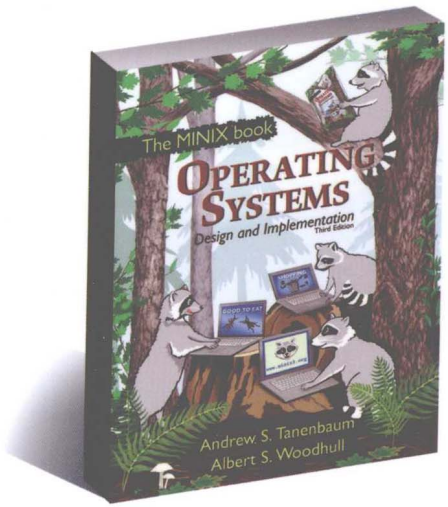
Operating Systems
Design and Implementation Third Edition

操作系统 设计与实现（第3版）

Andrew S. Tanenbaum
Albert S. Woodhull 著



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PREFACE

Most books on operating systems are strong on theory and weak on practice. This one aims to provide a better balance between the two. It covers all the fundamental principles in great detail, including processes, interprocess communication, semaphores, monitors, message passing, scheduling algorithms, input/output, deadlocks, device drivers, memory management, paging algorithms, file system design, security, and protection mechanisms. But it also discusses one particular system—MINIX 3—a UNIX-compatible operating system in detail, and even provides a source code listing for study. This arrangement allows the reader not only to learn the principles, but also to see how they are applied in a real operating system.

When the first edition of this book appeared in 1987, it caused something of a small revolution in the way operating systems courses were taught. Until then, most courses just covered theory. With the appearance of MINIX, many schools began to have laboratory courses in which students examined a real operating system to see how it worked inside. We consider this trend highly desirable and hope it continues.

It its first 10 years, MINIX underwent many changes. The original code was designed for a 256K 8088-based IBM PC with two diskette drives and no hard disk. It was also based on UNIX Version 7 As time went on, MINIX evolved in many ways: it supported 32-bit protected mode machines with large memories and hard disks. It also changed from being based on Version 7, to being based on the international POSIX standard (IEEE 1003.1 and ISO 9945-1). Finally, many

new features were added, perhaps too many in our view, but too few in the view of some other people, which led to the creation of Linux. In addition, MINIX was ported to many other platforms, including the Macintosh, Amiga, Atari, and SPARC. A second edition of the book, covering this system, was published in 1997 and was widely used at universities.

The popularity of MINIX has continued, as can be observed by examining the number of hits for MINIX found by Google.

This third edition of the book has many changes throughout. Nearly all of the material on principles has been revised, and considerable new material has been added. However, the main change is the discussion of the new version of the system, called MINIX 3. and the inclusion of the new code in this book. Although loosely based on MINIX 2, MINIX 3 is fundamentally different in many key ways.

The design of MINIX 3 was inspired by the observation that operating systems are becoming bloated, slow, and unreliable. They crash far more often than other electronic devices such as televisions, cell phones, and DVD players and have so many features and options that practically nobody can understand them fully or manage them well. And of course, computer viruses, worms, spyware, spam, and other forms of malware have become epidemic.

To a large extent, many of these problems are caused by a fundamental design flaw in current operating systems: their lack of modularity. The entire operatng system is typically millions of lines of C/C++ code compiled into a single massive executable program run in kernel mode. A bug in any one of those millions of lines of code can cause the system to malfunction. Getting all this code correct is impossible, especially when about 70% consists of device drivers, written by third parties, and outside the purview of the people maintaining the operating system.

With MINIX 3, we demonstrate that this monolithic design is not the only possibility. The MINIX 3 kernel is only about 4000 lines of executable code, not the millions found in Windows, Linux, Mac OS X, or FreeBSD. The rest of the system, including all the device drivers (except the clock driver), is a collection of small, modular, user-mode processes, each of which is tightly restricted in what it can do and with which other processes it may communicate.

While MINIX 3 is a work in progress, we believe that this model of building an operating system as a collection of highly-encapsulated user-mode processes holds promise for building more reliable systems in the future. MINIX 3 is especially focused on smaller PCs (such as those commonly found in Third-World countries and on embedded systems, which are always resource constrained). In any event, this design makes it much easier for students to learn how an operating system works than attempting to study a huge monolithic system.

The CD-ROM that is included in this book is a live CD. You can put it in your CD-ROM drive, reboot the computer, and MINIX 3 will give a login prompt within a few seconds. You can log in as *root* and give the system a try without first having to install it on your hard disk. Of course, it can also be installed on the hard disk. Detailed installation instructions are given in Appendix A.

As suggested above, MINIX 3 is rapidly evolving, with new versions being issued frequently. To download the current CD-ROM image file for burning, please go to the official Website: *www.minix3.org*. This site also contains a large amount of new software, documentation, and news about MINIX 3 development. For discussions about MINIX 3, or to ask questions, there is a USENET newsgroup: *comp.os.minix*. People without newsreaders can follow discussions on the Web at *http://groups.google.com/group/comp.os.minix*.

As an alternative to installing MINIX 3 on your hard disk, it is possible to run it on any one of several PC simulators now available. Some of these are listed on the main page of the Website.

Instructors who are using the book as the text for a university course can get the problem solutions from their local Prentice Hall representative. The book has its own Website. It can be found by going to *www.prenhall.com/tanenbaum* and selecting this title.

We have been extremely fortunate in having the help of many people during the course of this project. First and foremost, Ben Gras and Jorrit Herder have done most of the programming of the new version. They did a great job under tight time constraints, including responding to e-mail well after midnight on many occasions. They also read the manuscript and made many useful comments. Our deepest appreciation to both of them.

Kees Bot also helped greatly with previous versions, giving us a good base to work with. Kees wrote large chunks of code for versions up to 2.0.4, repaired bugs, and answered numerous questions. Philip Homburg wrote most of the networking code as well as helping out in numerous other useful ways, especially providing detailed feedback on the manuscript.

People too numerous to list contributed code to the very early versions, helping to get MINIX off the ground in the first place. There were so many of them and their contributions have been so varied that we cannot even begin to list them all here, so the best we can do is a generic thank you to all of them.

Several people read parts of the manuscript and made suggestions. We would like to give our special thanks to Gojko Babic, Michael Crowley, Joseph M. Kizza, Sam Kohn Alexander Manov, and Du Zhang for their help.

Finally, we would like to thank our families. Suzanne has been through this 16 times now. Barbara has been through it 15 times now. Marvin has been through it 14 times now. It's kind of getting to be routine, but the love and support is still much appreciated. (AST)

Al's Barbara has been through this twice now. Her support, patience, and good humor were essential. Gordon has been a patient listener. It is still a delight to have a son who understands and cares about the things that fascinate me. Finally, step-grandson Zain's first birthday coincides with the release of MINIX 3. Some day he will appreciate this. (ASW)

Andrew S. Tanenbaum
Albert S. Woodhull

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1

INTRODUCTION

Without its software, a computer is basically a useless lump of metal. With its software, a computer can store, process, and retrieve information; play music and videos; send e-mail, search the Internet; and engage in many other valuable activities to earn its keep. Computer software can be divided roughly into two kinds: system programs, which manage the operation of the computer itself, and application programs, which perform the actual work the user wants. The most fundamental system program is the **operating system**, whose job is to control all the computer's resources and provide a base upon which the application programs can be written. Operating systems are the topic of this book. In particular, an operating system called MINIX 3 is used as a model, to illustrate design principles and the realities of implementing a design.

A modern computer system consists of one or more processors, some main memory, disks, printers, a keyboard, a display, network interfaces, and other input/output devices. All in all, a complex system. Writing programs that keep track of all these components and use them correctly, let alone optimally, is an extremely difficult job. If every programmer had to be concerned with how disk drives work, and with all the dozens of things that could go wrong when reading a disk block, it is unlikely that many programs could be written at all.

Many years ago it became abundantly clear that some way had to be found to shield programmers from the complexity of the hardware. The way that has evolved gradually is to put a layer of software on top of the bare hardware, to manage all parts of the system, and present the user with an interface or **virtual**

machine that is easier to understand and program. This layer of software is the operating system.

The placement of the operating system is shown in Fig. 1-1. At the bottom is the hardware, which, in many cases, is itself composed of two or more levels (or layers). The lowest level contains physical devices, consisting of integrated circuit chips, wires, power supplies, cathode ray tubes, and similar physical devices. How these are constructed and how they work is the province of the electrical engineer.

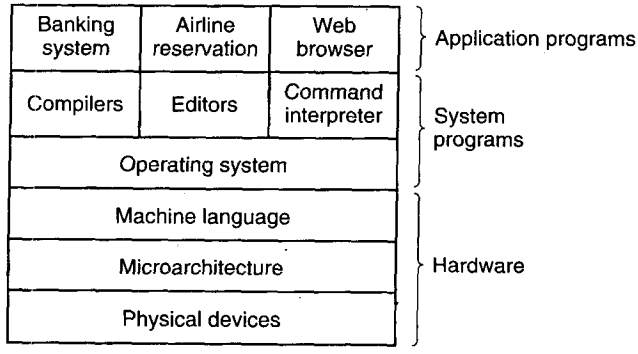

Figure 1-1. A computer system consists of hardware, system programs, and application programs.

Next comes the **microarchitecture level**, in which the physical devices are grouped together to form functional units. Typically this level contains some registers internal to the CPU (Central Processing Unit) and a data path containing an arithmetic logic unit. In each clock cycle, one or two operands are fetched from the registers and combined in the arithmetic logic unit (for example, by addition or Boolean AND). The result is stored in one or more registers. On some machines, the operation of the data path is controlled by software, called the **microprogram**. On other machines, it is controlled directly by hardware circuits.

The purpose of the data path is to execute some set of instructions. Some of these can be carried out in one data path cycle; others may require multiple data path cycles. These instructions may use registers or other hardware facilities. Together, the hardware and instructions visible to an assembly language programmer form the **ISA (Instruction Set Architecture)** This level is often called **machine language**.

The machine language typically has between 50 and 300 instructions, mostly for moving data around the machine, doing arithmetic, and comparing values. In this level, the input/output devices are controlled by loading values into special **device registers**. For example, a disk can be commanded to read by loading the values of the disk address, main memory address, byte count, and direction (read or write) into its registers. In practice, many more parameters are needed, and the

status returned by the drive after an operation may be complex. Furthermore, for many I/O (Input/Output) devices, timing plays an important role in the programming.

A major function of the operating system is to hide all this complexity and give the programmer a more convenient set of instructions to work with. For example, read block from file is conceptually much simpler than having to worry about the details of moving disk heads, waiting for them to settle down, and so on.

On top of the operating system is the rest of the system software. Here we find the command interpreter (shell), window systems, compilers, editors, and similar application-independent programs. It is important to realize that these programs are definitely not part of the operating system, even though they are typically supplied preinstalled by the computer manufacturer, or in a package with the operating system if it is installed after purchase. This is a crucial, but subtle, point. The operating system is (usually) that portion of the software that runs in **kernel mode** or **supervisor mode**. It is protected from user tampering by the hardware (ignoring for the moment some older or low-end microprocessors that do not have hardware protection at all). Compilers and editors run in **user mode**. If a user does not like a particular compiler, he† is free to write his own if he so chooses; he is not free to write his own clock interrupt handler, which is part of the operating system and is normally protected by hardware against attempts by users to modify it.

This distinction, however, is sometimes blurred in embedded systems (which may not have kernel mode) or interpreted systems (such as Java-based systems that use interpretation, not hardware, to separate the components). Still, for traditional computers, the operating system is what runs in kernel mode.

That said, in many systems there are programs that run in user mode but which help the operating system or perform privileged functions. For example, there is often a program that allows users to change their passwords. This program is not part of the operating system and does not run in kernel mode, but it clearly carries out a sensitive function and has to be protected in a special way.

In some systems, including MINIX 3, this idea is carried to an extreme form, and pieces of what is traditionally considered to be the operating system (such as the file system) run in user space. In such systems, it is difficult to draw a clear boundary. Everything running in kernel mode is clearly part of the operating system, but some programs running outside it are arguably also part of it, or at least closely associated with it. For example, in MINIX 3, the file system is simply a big C program running in user-mode.

Finally, above the system programs come the application programs. These programs are purchased (or written by) the users to solve their particular problems, such as word processing, spreadsheets, engineering calculations, or storing information in a database.

† "He" should be read as "he or she" throughout the book.

1.1 WHAT IS AN OPERATING SYSTEM?

Most computer users have had some experience with an operating system, but it is difficult to pin down precisely what an operating system is. Part of the problem is that operating systems perform two basically unrelated functions, extending the machine and managing resources, and depending on who is doing the talking, you hear mostly about one function or the other. Let us now look at both.

1.1.1 The Operating System as an Extended Machine

As mentioned earlier, the **architecture** (instruction set, memory organization, I/O, and bus structure) of most computers at the machine language level is primitive and awkward to program, especially for input/output. To make this point more concrete, let us briefly look at how floppy disk I/O is done using the NEC PD765 compatible controller chips used on many Intel-based personal computers. (Throughout this book we will use the terms "floppy disk" and "diskette" interchangeably.) The PD765 has 16 commands, each specified by loading between 1 and 9 bytes into a device register. These commands are for reading and writing data, moving the disk arm, and formatting tracks, as well as initializing, sensing, resetting, and recalibrating the controller and the drives.

The most basic commands are read and write, each of which requires 13 parameters, packed into 9 bytes. These parameters specify such items as the address of the disk block to be read, the number of sectors per track, the recording mode used on the physical medium, the intersector gap spacing, and what to do with a deleted-data-address-mark. If you do not understand this mumbo jumbo, do not worry; that is precisely the point—it is rather esoteric. When the operation is completed, the controller chip returns 23 status and error fields packed into 7 bytes. As if this were not enough, the floppy disk programmer must also be constantly aware of whether the motor is on or off. If the motor is off, it must be turned on (with a long startup delay) before data can be read or written. The motor cannot be left on too long, however, or the floppy disk will wear out. The programmer is thus forced to deal with the trade-off between long startup delays versus wearing out floppy disks (and losing the data on them).

Without going into the *real* details, it should be clear that the average programmer probably does not want to get too intimately involved with the programming of floppy disks (or hard disks, which are just as complex and quite different). Instead, what the programmer wants is a simple, high-level abstraction to deal with. In the case of disks, a typical abstraction would be that the disk contains a collection of named files. Each file can be opened for reading or writing, then read or written, and finally closed. Details such as whether or not recording should use modified frequency modulation and what the current state of the motor is should not appear in the abstraction presented to the user.