INSTRUCTOR'S MANUAL
TO ACCOMPANY

OPERATING SYSTEM CONCEPTS

FIFTH EDITION

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PREFACE

This volume is an instructor's manual for the fifth edition of *Operating System Concepts* by Abraham Silberschatz and Peter Galvin. It consists of answers to the exercises in the parent text and a set of review questions.

- **Answers to the Exercises**. Answers to the end-of-chapter exercises are given. In cases where the answer to a question involves a long program, algorithm development, or an essay, no answer is given, but simply the keywords "No Answer."
- **Review Questions**. Dr. James L. Boettler of South Carolina State College in Orangeburg, South Carolina has prepared a set of review questions, with answers and comments, on the first twelve chapters of the text. Originally prepared for the second edition of *Operating System Concepts,* the questions have been modified for each subsequent edition. These review questions provide immediate review and reinforcement of the key concepts, terms, and ideas of each chapter. The comments point out common errors made by the students in answering these questions. If the students understand the material, they should be able to answer these questions immediately. These questions can be used for review or as possible quiz questions.

Although we have tried to produce an instructor's manual that will aid all of the users of our book as much as possible, there can always be improvements (improved answers, additional questions, sample test questions, programming projects, alternative orders of presentation of the material, additional references, and so on). We invite you, both instructors and students, to help us in improving this manual. If you have better solutions to the exercises or other items which would be of use with *Operating System Concepts,* we invite you to send them to us for consideration in later editions of this manual. All contributions will, of course, be properly credited to their contributor.

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Chapter 1

INTRODUCTION

Chapter 1 is meant to introduce the general topic of operating systems. The student should be able to read Chapter 1 and go on. There are a handful of important concepts (multiprogramming, time sharing, distributed system, and so on). The development is meant to show *why* operating systems are what they are by showing *how* they developed. In operating systems, as in much of computer science, we are led to the present by the paths we took in the past and we can better understand both the present and the future by understanding the past.

Additional work that might be considered is learning about the particular systems that the students will have access to at your institution. This is still just a general overview, as specific interfaces are considered in Chapter 3.

Answers to Exercises

1.1 What are the three main purposes of an operating system?
Answer: There are several possible purposes of an operating system:

- To provide an environment for a computer user to execute programs on computer hardware in a convenient and efficient manner.
- To allocate the separate resources of the computer as needed to solve the problem given. The allocation process should be as fair and efficient as possible.
- As a control program it serves two major functions: 1) supervision of the execution of user programs to prevent errors and improper use of the computer, and 2) management of the operation and control of I/O devices.

1.2 List the four steps that are necessary to run a program on a completely dedicated machine.
Answer:

a. Reserve machine time.

b. Manually load program into memory.

c. Load starting address and begin execution.

d. Monitor and control execution of program from console.

1.3 An extreme method of spooling, known as *staging* a tape, is to read the entire contents of a magnetic tape onto disk before using it. Discuss the main advantage of such a scheme.

Answer: No I/O is needed while the data is being processed, so staging is more simple than spooling. All of the data are on-line before they are needed so a process can run at full speed. The disadvantage is that more time is spent, before the process starts, in loading the data, and more disk space is consumed in storing the entire tape contents.

1.4 In a multiprogramming and time-sharing environment, several users share the system simultaneously. This situation can result in various security problems.

a. What are two such problems?

b. Can we ensure the same degree of security in a time-shared machine as we have in a dedicated machine? Explain your answer.

Answer:

a. Stealing or copying one's programs or data; using system resources (CPU, memory, disk space, peripherals) without proper accounting.

b. Probably not, since any protection scheme devised by man can inevitably be broken by him, and the more complex the scheme, the more difficult it is to feel confident of its correct implementation.

1.5 What is the main advantage of multiprogramming?

Answer: Multiprogramming makes efficient use of the CPU by overlapping the demands for the CPU and its I/O devices from various users. It attempts to increase CPU utilization by always having something for the CPU to execute.

1.6 What are the main differences between operating systems for mainframe computers and personal computers?

Answer: Personal computer operating systems are not concerned with fair use, or maximal use, of computer facilities. Instead, they try to optimize the usefulness of the computer for an individual user, usually at the expense of efficiency. Consider how many CPU cycles are used by graphical user interfaces (GUIs). Mainframe operating systems need more complex scheduling and I/O algorithms to keep the various system components busy.

1.7 Define the essential properties of the following types of operating systems:

a. Batch

b. Interactive

c. Time sharing

d. Real time

e. Distributed

Answer:

a. **Batch**. Jobs with similar needs are batched together and run through the computer as a group by an operator or automatic job sequencer. Performance is increased by attempting to keep CPU and I/O devices busy at all times through buffering, off-line operation, spooling, and multiprogramming. Batch is good for executing large jobs that need little interaction; it can be submitted and picked up later.

b. **Interactive**. Composed of many short transactions where the results of the next transaction may be unpredictable. Response time needs to be short (seconds) since the user submits and waits for the result.

c. **Time sharing**. Uses CPU scheduling and multiprogramming to provide economical interactive use of a system. The CPU switches rapidly from one user to another. Instead of having a job defined by spooled card images, each program reads its next control card from the terminal, and output is normally printed immediately to the screen.

d. **Real time**. Often used in a dedicated application. The system reads information from sensors and must respond within a fixed amount of time to ensure correct performance.

e. **Distributed**. Distributes computation among several physical processors. The processors do not share memory or a clock. Instead, each processor has its own local memory. They communicate with each other through various communication lines, such as a high-speed bus or telephone line.

1.8 We have stressed the need for an operating system to make efficient use of the computing hardware. When is it appropriate for the operating system to forsake this principle and to "waste" resources? Why is such a system not really wasteful?

Answer: Single-user systems should maximize use of the system for the user. A GUI might "waste" CPU cycles but it optimizes the user's interaction with the system.

1.9 Under what circumstances would a user be better off using a time-sharing system, rather than a personal computer or single-user workstation?

Answer: When there are few other users, the task is large, and the hardware is fast, time-sharing makes sense. The full power of the system can be brought to bear on the user's problem. The problem can be solved faster than on a personal computer. Another case is when there are lots of other users needing resources at the same time.

A personal computer is best when the job is small enough to be executed reasonably on it, and when performance is sufficient to execute the program to the user's satisfaction.

1.10 Describe the differences between symmetric and asymmetric multiprocessing. What are three advantages and one disadvantage of multiprocessor systems?

Answer: Symmetric multiprocessing treats all processors as equals, and I/O can be processed on any CPU. Asymmetric multiprocessing has one master CPU and the remainder CPUs are slaves. The master distributes tasks among the slaves, and I/O is usually done by the master only. Multiprocessors can save money, by not duplicating power supplies, housings, and peripherals. They can execute programs more quickly, and can have increased reliability. They are also more complex in both hardware and software than uniprocessor systems.

1.11 Why are distributed systems desirable?

Answer: Distributed systems can provide resource sharing, computation speedup, increased reliability, and the ability to communicate with remote sites.

1.12 What is the main difficulty that a programmer must overcome in writing an operating system for a real-time environment?

Answer: The main difficulty is keeping the operating system within the fixed time constraints of a real-time system. If the system does not complete a task in a certain time, it could cause a breakdown of the entire system it is running. Therefore when writing an operating system for a real-time system, the writer must be sure that his scheduling schemes don’t allow response time to exceed the time constraint.

■ Review Questions

1.1 True/False: An operating system can be viewed as "resource allocator" to control various I/O devices and user programs.

Answer: True

1.2 What is the fundamental goal of computer systems?

Answer: To execute user programs and solve user problems.

1.3 Define operating systems in terms of what they do.

Answer: Their primary goal is convenience of the user; the secondary goal is efficient operation and allocation of all resources.

1.4 Describe how the earliest computers were used.

Answer: The programmer himself operated the computer by flipping switches. He had to sign up for free time.

1.5 What problems were involved in these earliest computers?

Answer: The user had to guess the amount of time needed to complete his job, fairly accurately, to avoid wasting machine time, and still allow enough time to complete the job.

1.6 What software was added to increase user efficiency?

Answer: Libraries of common functions, device drivers, assembly language, compilers.

1.7 What effect did adding I/O devices have on software?

Answer: Creation of software libraries shared by all users, especially for input–output subroutines.

1.8 What factors contributed to the setup time for a job? List them.

Answer:

a. Load loader tape.

b. Load compiler tape.

c. Load source program.

d. Execute compiler with output going to tape.

e. Rewind each tape.

f. If output of compiler was assembly language, load assembler.

g. Rewind tapes.

h. Execute assembler with object output to tape.

i. Rewind tapes.

j. Load the object program from tape.

k. Execute the program with output going to paper tape.

l. Run paper tape output through teletype to get printed copy.

Note: On some systems, the loader had to be reloaded after many of the above steps.

1.9 What is a simple batch system?

Answer: A professional computer operator (or machine) groups jobs by characteristics and runs groups of similar jobs together, efficiently.

1.10 Why use simple batch systems, in preference to early systems?

Answer: Less setup time, and thus less idle time of the computer.

1.11 What is “automatic job sequencing”?

Answer: System proceeds from one job to the next without human intervention.

1.12 Why have automatic job sequencing?

Answer: To avoid the delays inherent in having the operator changing jobs, and doing things manually.

1.13 What is the purpose of the “resident monitor”?

Answer: To perform orderly and efficient automatic job sequencing, regardless of errors that might arise.

1.14 What were control cards used for?

Answer: To let monitor know what resources are needed for current job, such as compiler, linker, data, etc., when to use them, and with which file; and to tell monitor when it reaches end of job.

1.15 List parts of the monitor.

Answer: Control card interpreter, device drivers, loader.

1.16 Compare speeds of various I/O devices, in characters / second.

Answer:

humans	0.5 to 5 characters / second
paper tape	10 characters / second
cards	1600 characters / second
magnetic tape	160,000 characters / second

1.17 Describe two kinds of off-line operations.

Answer:

a. Cards copied to magnetic tape, which was then mounted on computer; output of computer was dumped to magnetic tape, which was then mounted for output to a printer.

b. Satellite computers read cards onto magnetic tape, which could transfer information to the main computer without remounting.

1.18 Describe two approaches to off-line processing.

Answer:

a. Data is read from cards onto magnetic tapes, which are in turn mounted manually on the main system. Printer output from the main system is saved on magnetic tape, which is then mounted manually on a tape reader attached to a line printer.

b. Data is read from cards onto magnetic tapes. But the tapes are not removed from their drives. Instead, a small computer reads them and sends the information to the main system. Similarly with output.

Note: Main difference here is that data was manually exchanged between main computer and off-line system.

1.19 What is device independence?

Answer: The feature of systems that allows one input device to be replaced by another without changes in the users' programs. Similarly with output. Thus, an old model card reader can be replaced with a new model; the old device driver programs are replaced by new ones; user programs need not be changed (though they may need to be relinked).

Note: Many students respond that it is the ability to use different devices. This is false. You can write a FORTRAN II program to read cards and print to a line printer, two different devices; yet this does not imply device independence.

1.20 What were the advantages of off-line operations?

Answer:

a. Main computer no longer constrained by speed of card reader.

b. Application programs used logical I/O devices instead of physical I/O devices; programs didn't have to be rewritten when new I/O devices replaced old ones.

1.21 How have disk systems helped solved problems inherent in off-line systems?

Answer: Off-line systems use magnetic tape. The system cannot read data from one end of the tape while the card reader writes data on the other end; it takes about 5 minutes to rewind the tape fully. With disks, it takes only milliseconds to alternate from the portion of the disk used for input and the portion for output.

1.22 What is spooling?

Answer: An acronym for "Simultaneous Peripheral Operation On-Line." It uses the disk as a large buffer for outputting data to line printers and other devices (like microfilm). It can also be used for input, but is generally used for output. Its main use is to prevent two users from alternately printing lines to the line printer on the same page, getting their output completely mixed together. It also helps in reducing idle time and overlapped I/O and CPU.

1.23 How do I/O-bound and CPU-bound programs differ?

Answer:

- In I/O-bound programs, the CPU remains idle much of the time.
- In CPU-bound programs, the I/O processor remains idle.

Note: I/O is never "faster" than CPU.

1.24 What is multiprogramming?

Answer: In multiprogramming, several programs are in memory concurrently; the system switches among the programs for efficient processing, and minimal idle time.

Note: Many students claim multiprogramming "always" keeps CPU and I/O devices busy; this is false; what is the computer to do at 3 AM Sunday morning, when there's no job to run?

1.25 Define batch systems in terms of interaction.

Answer: They are essentially devoid of interaction between user and program. All problems must be anticipated, and can't be corrected on-line.

1.26 In what ways are batch systems inconvenient for users?

Answer: Users can't interact with their jobs to fix problems. They must anticipate problems or else debugging could be a mess with machine-language dumps. There may also be long turnaround times.

1.27 What is time-sharing?
Answer: Using scheduling and multiprogramming to provide an economical interactive system of two or more users.

1.28 What are the main advantages of a time-share system?
Answer: Interaction with computer while program is running, short response times (usually less than 10 seconds).

1.29 How is time-sharing usually implemented?
Answer: Each user is given a brief time-slice for her job, in round-robin fashion. Her job continues until the time-slice ends. Then her job stops, until it is her turn again.

1.30 How do MULTICS and UNIX differ?
Answer:

- MULTICS was a time-sharing system created on a large mainframe GE computer (since then taken over by Honeywell), by GE, by Bell Labs, and by faculty at MIT. It was very flexible, and oriented toward programmers.
- UNIX was inspired by MULTICS; but it was designed by Ritchie and Thompson in 1974 at Bell Labs for use on minicomputers, like the PDP-11. It was designed for program development, using a device-independent file system.

1.31 What is a multiprocessor system?
Answer: A system with two or more CPUs.

1.32 What is a master / slave processor system?
Answer: A master computer controls the actions of various slave computers.

1.33 What does RJE stand for?
Answer: Remote Job Entry.

1.34 What is a real-time system?
Answer: A system used to control a dedicated application.

1.35 How does a real-time system differ from time-share?
Answer: In time-sharing, fast response is desirable, but not required. In real-time systems, processing *must* be completed within certain time constraints appropriate for the system.

1.36 List several examples of real-time systems.
Answer:

a. Control of a nuclear reactor, to prevent chain reaction.
b. Control of a space ship, to avoid collision with meteors.
c. Control of manufacturing equipment, such as lathes, canners, etc.
d. Detecting patients' conditions in Intensive Care Units in hospitals.
e. Collecting data on cosmic rays in physics research.

Chapter 2

COMPUTER-SYSTEM STRUCTURES

Chapter 2 discusses the general structure of computer systems. It may be a good idea to review the basic concepts of machine organization and assembly language programming. The students should be comfortable with the concepts of memory, CPU, registers, I/O, interrupts, instructions, and the instruction execution cycle. Since the operating system is the interface between the hardware and user programs, a good understanding of operating systems requires an understanding of both hardware and programs.

■ Answers to Exercises

2.1 *Prefetching* is a method of overlapping the I/O of a job with that job's own computation. The idea is simple. After a read operation completes and the job is about to start operating on the data, the input device is instructed to begin the next read immediately. The CPU and input device are then both busy. With luck, by the time that the job is ready for the next data item, the input device will have finished reading that data item. The CPU can then begin processing the newly read data, while the input device starts to read the following data. A similar idea can be used for output. In this case, the job creates data that are put into a buffer until an output device can accept them.

Compare the prefetching scheme with the spooling scheme, where the CPU overlaps the input of one job with the computation and output of other jobs.

Answer: Prefetching is a user-based activity, while spooling is a system-based activity. Spooling is a much more effective way of overlapping I/O and CPU operations.

2.2 How does the distinction between monitor mode and user mode function as a rudimentary form of protection (security) system?

Answer: By establishing a set of privileged instructions that can be executed only when in the monitor mode, the operating system is assured of controlling the entire system at all times.

2.3 What are the differences between a trap and an interrupt? What is the use of each function?

Answer: An interrupt is a hardware-generated change-of-flow within the system. An interrupt handler is summoned to deal with the cause of the interrupt; control is then returned to the interrupted context and instruction. A trap is a software-generated interrupt. An interrupt can be used to signal the completion of an I/O to obviate the need for device polling. A trap can be used to call operating system routines or to catch arithmetic errors.

2.4 For what types of operations is DMA useful? Explain your answer.
Answer: DMA is useful for transferring large quantities of data between memory and devices. It eliminates the need for the CPU to be involved in the transfer, allowing the transfer to complete more quickly and the CPU to perform other tasks concurrently.

2.5 Which of the following instructions should be privileged?

a. Set value of timer.

b. Read the clock.

c. Clear memory.

d. Turn off interrupts.

e. Switch from user to monitor mode.

Answer: The following instructions should be privileged:

a. Set value of timer.

b. Clear memory.

c. Turn off interrupts.

d. Switch from user to monitor mode.

2.6 Some computer systems do not provide a privileged mode of operation in hardware. Consider whether it is possible to construct a secure operating system for these computers. Give arguments both that it is and that it is not possible.
Answer: An operating system for a machine of this type would need to remain in control (or monitor mode) at all times. This could be accomplished by two methods:

a. Software interpretation of all user programs (like some BASIC, APL, and LISP systems, for example). The software interpreter would provide, in software, what the hardware does not provide.

b. Require that all programs be written in high-level languages so that all object code is compiler-produced. The compiler would generate (either in-line or by function calls) the protection checks that the hardware is missing.

2.7 Some early computers protected the operating system by placing it in a memory partition that could not be modified by either the user job or the operating system itself. Describe two difficulties that you think could arise with such a scheme.
Answer: The data required by the operating system (passwords, access controls, accounting information, and so on) would have to be stored in or passed through unprotected memory and thus be accessible to unauthorized users.

2.8 Protecting the operating system is crucial to ensuring that the computer system operates correctly. Provision of this protection is the reason behind dual-mode operation, memory protection, and the timer. To allow maximum flexibility, however, we would also like to place minimal constraints on the user. The following is a list of operations that are normally protected. What is the *minimal* set of instructions that must be protected?

a. Change to user mode.

b. Change to monitor mode.
c. Read from monitor memory.
d. Write into monitor memory.
e. Fetch an instruction from monitor memory.
f. Turn on timer interrupt.
g. Turn off timer interrupt.

Answer: The minimal set of instructions that must be protected are:

a. Change to monitor mode.
b. Read from monitor memory.
c. Write into monitor memory.
d. Turn off timer interrupt.

2.9 When are caches useful? What problems do they solve? What problems do they cause? If a cache can be made as large as the device for which it is caching (for instance, a cache as large as a disk), why not make it that large and eliminate the device?

Answer: Caches are useful when two or more components need to exchange data, and the components perform transfers at differing speeds. Cahces solve the transfer problem by providing a buffer of intermediate speed between the components. If the fast device finds the data it needs in the cache, it need not wait for the slower device. The data in the cache must be kept consistent with the data in the components. If a component has a data value change, and the datum is also in the cache, the cache must also be updated. This is especially a problem on multiprocessor systems where more than one process may be accessing a datum. A component may be eliminated by an equal-sized cache, but only if: a) the cache and the component have equivalent state-saving capacity (that is, if the component retains its data when electricity is removed, the cache must retain data as well), and b) the cache is affordable, because faster storage tends to be more expensive.

2.10 Writing an operating system that can operate without interference from malicious or undebugged user programs requires some hardware assistance. Name three hardware aids for writing an operating system, and describe how they could be used together to protect the operating system.

Answer:

a. Monitor / user mode
b. Privileged instructions
c. Timer
d. Memory protection

■ Review Questions

2.1 How is an interrupt executed?
Answer: The I/O driver sends a signal through a special interrupt line to the CPU when it has finished with an I/O request.

2.2 What is an interrupt vector?
Answer: A list giving the starting addresses of each interrupt service routine.

2.3 In what ways do systems treat slow and fast devices differently?
Answer: For slow devices, each character transferred causes an interrupt. For fast devices, each block of characters transferred causes an interrupt.

2.4 What is DMA?
Answer: Direct Memory Access (DMA) allows transfers of blocks of data between memory and I/O devices without intervention of the CPU, by making the transfers in between CPU instruction executions (called "interleaving").

2.5 List some special problems a programmer must concern himself with while writing I/O routines with buffers.
Answer: Can't allow interrupt to occur while moving a record into or out of a buffer. Can't transfer data into a filled buffer. Can't transfer data out of an empty buffer.

2.6 List operations that the monitor considers illegal, and describe why each must be considered illegal.
Answer:

a. Programming errors, such as illegal instruction, addressing fault.
b. Job reads cards for next users' jobs reading control cards; or else one job will interfere with the next.
c. Halting the computer.
d. Masking the interrupt so that none can occur. Turning on interrupts; or else job will interfere with I/O.
e. Changing mode from user to system; or else user can control system.
f. Using memory outside user area; invasion of privacy.
g. Modifying interrupt vectors in monitor; could crash system.
h. Accessing monitor memory; invasion of privacy.

2.7 What resources must be protected by the operating system?
Answer: I/O, the monitor, memory, CPU

2.8 Describe the magnetic properties of disks.
Answer: Disks are flat circular-shaped platters with magnetic material on both surfaces. They have concentric tracks where information is stored. Each track is divided up into sectors. The disks spin to allow read/write heads to access each part, typically 5 rev/sec for floppies to 60 rev/sec for hard disks.

2.9 List kinds of disks.
Answer:

a. Fixed head disk: has one read/write head for each track.

b. Moving head disk: one read / write head per surface; it moves back and forth to access the various tracks.

c. Multiplatter disks: several disks in one cover, all driven by the same motor.

d. Removable cartridge: allows disks to be swapped.

e. Hard disks: uses rigid aluminum platters covered with magnetic material.

f. Floppy disks: uses flexible material like in *Time-Life* sample records, encased in cardboard.

g. RAM disks: not really a disk; semiconductor memory set up to emulate a disk.

2.10 What is a sector? track?
Answer:

- Sector — smallest block that can be read or written on a disk.
- Track — collection of sectors all on same circumference on a single surface.

2.11 What is a disk controller?
Answer: A separate board installed in the computer chassis to control and interact with each disk drive attached to it.

2.12 What is a drum?
Answer: Effectively, a single disk with only one cylinder. It is a cylinder-shaped box that revolves on its axis, with the read / write surface around the circumference, with many tracks all of the same radius.

2.13 How does the operating system determine what mode it is in?
Answer: One bit gives the present state — the monitor / user-mode bit.

2.14 List ways a user can take control of a system if memory is not protected.
Answer:

a. Alter an interrupt vector entry to point to his own program area. This would give him control of the system while system is in monitor mode.

b. Alter part of the interrupt service routine to jump to his program, again giving him privileged access to all instructions.

2.15 How can we prevent users from accessing other users' programs and data?
Answer: Introduce base and limit registers that hold the smallest legal physical memory address, and the size of the range, respectively. As a user's job is started, the operating system loads these registers; if the program goes beyond these addresses, it is aborted. If another job starts up, these registers are reset for the new job.

2.16 How can the operating system detect an infinite loop in a program?
Answer: A timer (hardware) is added to system. Each user is allowed some predetermined time of execution (not all users are given same amount). If user exceeds these time limits, the program is aborted via an interrupt.

2.17 List some categories of privileged instructions.
Answer:

a. I / O

b. Modifying base and limit registers

c. Modifying timer
d. Halt
e. Turning interrupt enable off
f. Changing monitor / user-mode bit

Chapter 3

OPERATING-SYSTEM STRUCTURES

Chapter 3 is concerned with the operating system interfaces that users (or at least programmers) actually see: control cards and system calls. The treatment is somewhat vague since more detail requires picking a specific system to discuss. This chapter is best supplemented with exactly this detail for the specific system the students have at hand. They should study the control card (or command) semantics and syntax; ideally they should study the system calls and write some programs making system calls. This chapter also ties together several important concepts including layered design, virtual machines, system design and implementation, system generation, and the policy / mechanism difference.

■ Answers to Exercises

3.1 What are the five major activities of an operating system in regard to process management?
Answer:

- The creation and deletion of both user and system processes
- The suspension and resumption of processes
- The provision of mechanisms for process synchronization
- The provision of mechanisms for process communication
- The provision of mechanisms for deadlock handling

3.2 What are the three major activities of an operating system in regard to memory management?
Answer:

- Keep track of which parts of memory are currently being used and by whom.
- Decide which processes are to be loaded into memory when memory space becomes available.
- Allocate and deallocate memory space as needed.

3.3 What are the three major activities of an operating system in regard to secondary-storage management?

Answer:

- Free-space management.
- Storage allocation.
- Disk scheduling.

3.4 What are the five major activities of an operating system in regard to file management?

Answer:

- The creation and deletion of files
- The creation and deletion of directories
- The support of primitives for manipulating files and directories
- The mapping of files onto secondary storage
- The backup of files on stable (nonvolatile) storage media

3.5 What is the purpose of the command interpreter? Why is it usually separate from the kernel?

Answer: It reads commands from the user or from a file of commands and executes them, usually by turning them into one or more system calls. It is usually not part of the kernel since the command interpreter is subject to changes.

3.6 List five services provided by an operating system. Explain how each provides convenience to the users. Explain also in which cases it would be impossible for user-level programs to provide these services.

Answer:

- **Program execution**. The operating system loads the contents (or sections) of a file into memory and begins its execution. A user-level program could not be trusted to properly allocate CPU time.
- **I/O operations**. Disks, tapes, serial lines, and other devices must be communicated with at a very low level. The user need only specify the device and the operation to perform on it, while the system converts that request into device or controller specific commands. User-level programs cannot be trusted to only access devices they should have access to, and to only access them when they are otherwise unused.
- **File-system manipulation**. There are many details in file creation, deletion, allocation, and naming that users should not have to perform. Blocks of disk space are used by files and must be tracked. Deleting a file requires removing the name file information and freeing the allocated blocks. Protections must also be checked to assure proper file access. User programs could ensure neither adherence to protection methods nor could they be trusted to allocate only free blocks and deallocate blocks on file deletion.
- **Communications**. Message passing between systems requires messages be turned into packets of information, sent to the network controller, transmitted across a communications medium, and reassembled by the destination system. Packet ordering and data correction must take place. Again, user programs might not coordinate access to the network device, or they may receive packets destined for other processes.

- **Error detection**. Error detection occurs at both the hardware and software levels. At the hardware level, all data transfers must be inspected to ensure that data have not been corrupted in transit. All data on media must be checked to be sure they have not changed since they were written to the media. At the software level, media must be checked for data consistency; for instance, do the number of allocated and unallocated blocks of storage match the total number on the device. There, errors are frequently process-independent (for instance, the corruption of data on a disk), so there must be a global program (the operating system) that handles all types of errors. Also, by having errors processed by the operating system, processes need not contain code to catch and correct all the errors possible on a system.

3.7 What is the purpose of system calls?

Answer: System calls allow user-level processes to request services of the operating system.

3.8 What is the purpose of system programs?

Answer: System programs can be thought of as bundles of useful system calls. They provide basic functionality to users so users do not need to write their own programs to solve common problems.

3.9 What is the main advantage of the layered approach to system design?

Answer: As in all cases of modular design, designing an operating system in a modular way has several advantages. The system is easier to debug and modify because changes affect only limited sections of the system rather than touching all sections of the operating system. Information is kept only where it is needed and is accessible only within a defined and restricted area, so any bugs affecting that data must be limited to a specific module or layer.

3.10 What is the main advantage for an operating-system designer of using a virtual-machine architecture? What is the main advantage for a user?

Answer: The system is easy to debug, and security problems are easy to solve. Virtual machines also provide a good platform for operating system research since many different operating systems may run on one physical system.

3.11 Why is the separation of mechanism and policy a desirable property?

Answer: Mechanism and policy must be separate to ensure that systems are easy to modify. No two system installations are the same, so each installation may want to tune the operating system to suit its needs. With mechanism and policy separate, the policy may be changed at will while the mechanism stays unchanged. This arrangement provides a more flexible system.

3.12 Consider the experimental Synthesis operating system, which has an assembler incorporated within the kernel. To optimize system-call performance, the kernel assembles routines within kernel space to minimize the path the system call must take through the kernel. This approach is the antithesis of the layered approach, in which the path through the kernel is extended so that building the operating system is made easier. Discuss the pros and cons of this approach to kernel design and to system-performance optimization.

Answer: Synthesis is impressive due to the performance it achieves through on-the-fly compilation. Unfortunately, it is difficult to debug problems within the kernel due to the fluidity of the code. Also, such compilation is system specific, making Synthesis difficult to port (a new compiler must be written for each architecture).

Review Questions

3.1 List system service functions provided for the convenience of the programmer. Tell what each does.
Answer:

Program execution	loads and executes programs, allows debugging
I/O operations	does all read and write operations
File system management	allows you to create, delete, open files, etc.
Communications	allows processes to communicate with each other
Error detection	CPU, hardware, instructions, device errors

3.2 List system service functions provided for efficient operation of the system.
Answer:

- Resource allocation
- Accounting
- Protection

3.3 List several systems-programming languages.
Answer: C, Bliss, PL/360, Pascal, assembly

3.4 How do systems-programming languages differ from other high-level languages?
Answer: Systems-programming languages allow system calls directly; they have provisions for accessing hardware components, such as registers. Other high-level languages don't.

3.5 List system calls used in a typical file-processing PL/I program.
Answer: Get, put, signal(finish), open, close. In more detail:

a. Put prompt message
b. Get file names
c. Open files
d. On error condition
e. Put error message
f. Write or Put into file created
g. On end-of-file
h. Put error message
i. Read or Get file
j. Put or Write file
k. Put all-done message
l. Close both files
m. Delete source file
n. Signal (*Finish*)

3.6 Describe three methods for passing parameters needed by system calls.
Answer:

a. Pass parameters in registers

b. Registers pass starting addresses of blocks of parameters

c. Parameters can be placed, or *pushed*, onto the *stack* by the program, and *popped* off the stack by the operating system.

3.7 List five or more functions to control processes and jobs.
Answer:

- Set error level
- Load / link / execute program
- Create new process
- Get / set process attributes
- Terminate process
- Wait for specific event or time
- Dump memory
- Trace instructions
- Create time profile

3.8 List eight or more functions for file manipulation.
Answer: Create, delete, open, close, read, write, and reposition files, get / set file attributes

3.9 List debugging aids for programmers.
Answer:

- Dump memory
- Trace instructions
- Create time profile

3.10 What is a time profile?
Answer: Shows amount of time executed by each instruction or block of instructions.

3.11 List categories of systems programs.
Answer:

- File manipulation
- Get status information
- Modify files
- Programming language support
- Program loading / execution
- Communications
- Application programs

3.12 What is a command interpreter? By what other names is it known?
Answer: Program that interprets the commands you type in at terminal, or enter through a batch file; gets and executes next user-specified command. Names: control card interpreter, command line interpreter, console command processor, shell.

3.13 How can command interpreters be implemented?
Answer:

a. Whole procedures in memory.

b. Procedure calls programs into memory from disk.

Chapter 4

PROCESSES

In this chapter we introduce the concept of a process and the notion of concurrent execution. Those are at the very heart of modern operating systems. A process is is a program in execution and is the unit of work in a modern time-sharing system. Such a system consists of a collection of processes: Operating-system processes executing system code, and user processes executing user code. All these processes can potentially execute concurrently, with the CPU (or CPUs) multiplexed among them. By switching the CPU between processes, the operating system can make the computer more productive. We also discuss the notion of a thread (light-weight process) and interprocess communication (IPC).

■ Answers to Exercises

4.1 Several popular microcomputer operating systems provide little or no means of concurrent processing. Discuss the major complications that concurrent processing adds to an operating system.

Answer:

- A method of time sharing must be implemented to allow each of several processes to have access to the system. This method involves the preemption of processes that do not voluntarily give up the CPU (by using a system call, for instance) and the kernel being reentrant (so more than one process may be executing kernel code concurrently).
- Processes and system resources must have protections and must be protected from each other. Any given process must be limited in the amount of memory it can use and the operations it can perform on devices like disks.
- Care must be taken in the kernel to prevent deadlocks between processes, so processes aren't waiting for each other's allocated resources.

4.2 Describe the differences among short-term, medium-term, and long-term scheduling.

Answer:

- **Short-term** (CPU scheduler) - selects from jobs in memory, those jobs which are ready to execute, and allocates the CPU to them.
- **Medium-term** - used especially with time-sharing systems as an intermediate scheduling level. A swapping scheme is implemented to remove partially run programs from memory and reinstate them later to continue where they left off.
- **Long-term** (job scheduler) - determines which jobs are brought into memory for processing.

The primary difference is in the frequency of their execution. The short-term must select a new process quite often. Long-term is used much less often since it handles placing jobs in the system, and may wait a while for a job to finish before it admits another one.

4.3 A DECSYSTEM-20 computer has multiple register sets. Describe the actions of a context switch if the new context is already loaded into one of the register sets. What else must happen if the new context is in memory rather than a register set, and all the register sets are in use?

Answer: The CPU current-register-set pointer is changed to point to the set containing the new context, which takes very little time. If the context is in memory, one of the contexts in a register set must be chosen and moved to memory, and the new context must be loaded from memory into the set. This process takes a little more time than on systems with one set of registers, depending on how a replacement victim is selected.

4.4 What two advantages do threads have over multiple processes? What major disadvantage do they have? Suggest one application that would benefit from the use of threads, and one that would not.

Answer: Threads are very inexpensive to create and destroy, and they use very little resources while they exist. They do use CPU time for instance, but they don't have totally separate memory spaces. Unfortunately, threads must "trust" each other to not damage shared data. For instance, one thread could destroy data that all the other threads rely on, while the same could not happen between processes unless they used a system feature to allow them to share data. Any program that may do more than one task at once could benefit from multitasking. For instance, a program that reads input, processes it, and outputs it could have three threads, one for each task. "Single-minded" processes would not benefit from multiple threads; for instance, a program that displays the time of day.

4.5 What resources are used when a thread is created? How do they differ from those used when a process is created?

Answer: A context must be created, including a register set storage location for storage during context switching, and a local stack to record the procedure call arguments, return values, and return addresses, and thread-local storage. A process creation results in memory being allocated for program instructions and data, as well as thread-like storage. Code may also be loaded into the allocated memory.

4.6 Describe the actions taken by a kernel to switch context

a. Among threads.

b. Among processes.

Answer:

a. The thread context must be saved (registers and accounting if appropriate), and another thread's context must be loaded.

b. The same as (a), plus the memory context must be stored and that of the next process must be loaded.

4.7 What are the differences between user-level threads and kernel-supported threads? Under what circumstances is one type “better” than the other?

Answer: User-level threads have no kernel support, so they are very inexpensive to create, destroy, and switch among. However, if one blocks, the whole process blocks. Kernel-supported threads are more expensive because system calls are needed to create and destroy them and the kernel must schedule them. They are more powerful because they are independently scheduled and block individually.

4.8 The correct producer–consumer algorithm presented in Section 4.6 allows only $n - 1$ buffers to be full at any time. Modify the algorithm to allow all the buffers to be utilized fully.

Answer: The shared data structures are as in the solution presented in Section 4.6, with the addition of:

```
var full: array[0..n-1] of boolean
```

initially *full*[*i*] = *false*, for all *i*.

The producer process has a local variable *nextp* in which the new item to be produced is stored:

```
repeat
      ...
    produce an item in nextp
      ...
    while full[in] do skip;
    buffer[in] := nextp;
    full[in] := true;
    in := in+1 mod n;
until false;
```

The code for the consumer process can be modified as follows:

```
repeat
    while not full[out] do skip;
    nextc := buffer[out];
    full[out]:= false;
    out := out+1 mod n;
      ...
    consume the item in nextc
      ...
until false;
```

4.9 Consider the interprocess-communication scheme where mailboxes are used.

a. Suppose a process *P* wants to wait for two messages, one from mailbox *A* and one from mailbox *B*. What sequence of **send** and **receive** should it execute?

b. What sequence of **send** and **receive** should *P* execute if *P* wants to wait for one message either from mailbox *A* or from mailbox *B* (or from both)?

c. A **receive** operation makes a process wait until the mailbox is nonempty. Either devise a scheme that allows a process to wait until a mailbox is empty, or explain why such a scheme cannot exist.

Answer: No Answer

4.10 Consider an operating system that supports both the IPC and RPC schemes. Give examples of problems that could be solved with each type of scheme. Explain why each problem is best solved by the method that you specify.
Answer: No Answer

■ Review Questions

4.1 What is a process?
Answer: A program in execution.

4.2 What is a PCB? (See Figure 4.2.)
Answer: Process control block. It contains various data structures.

4.3 List some of the queues on a typical system.
Answer: Ready, run, I/O.

4.4 How are these queues typically implemented?
Answer: FIFO queues, trees, linked-lists.

4.5 How many device queues are there on a system?
Answer: One for each device.

4.6 What does the long-term scheduler do?
Answer: Determines which jobs belong in the current mix of running/waiting jobs.

4.7 What does the short-term scheduler do?
Answer: Determines which of the current jobs should run in the next CPU burst.

4.8 Which scheduler must work very fast in order not to waste significant CPU time? Which can be slow?
Answer: Fast: short-term. Slow: long-term.

4.9 What is the "degree of multiprogramming?"
Answer: Number of jobs in the current mix of running/waiting jobs.

4.10 When is the long-term scheduler invoked?
Answer: When a job is completed, or when the degree of multiprogramming hasn't yet been reached.

4.11 True/False: The long-term scheduler selects a group of I/O-bound jobs or a group of CPU-bound programs for subsequent activity. Explain.
Answer: False. It selects a mix of jobs for efficient machine utilization.

4.12 What is time sharing? What kind of scheduling does it involve?
Answer: Time sharing is many users interactively using a system "simultaneously;" each user gets a share of CPU-time, after other users have gotten their share. It uses medium-term scheduling, such as round-robin for the foreground. Background can use a different scheduling technique.

4.13 Explain the meaning of: "time sharing depends on negative feedback of the users for speedy operation."
Answer: Users who are impatient with the long response time will log off, resulting in fewer users on the system, with faster response time.

4.14 What is swapping?
Answer: Copying a process out of memory onto a fast disk or drum, to allow space for other active processes; it will be copied back into memory when space is ample.

4.15 What is a context switch?
Answer: The time needed to switch from one job to another.

4.16 Describe five implementations of the create-new-process mechanism.
Answer:

a. Parent continues executing.

b. Parent stops executing until children are done.

c. Parent and children share all variables.

d. Children share only a subset of parent's variables.

e. Parents and children share no common resources.

4.17 Describe the producer / consumer problem.
Answer: The consumer can't be allowed to use a result until the producer has created that result, and the producer can't be allowed to create results if the buffers are all full.

4.18 Give examples of producer / consumer pairs.
Answer: compiler / linker, linker / loader, card-reader / line-printer

4.19 How do you implement a circular array?
Answer: Using mod arithmetic, like in clocks.
Note: Several students have said by using linked lists; not so, authors *replace* the circular array with a linked list.

4.20 How do you determine if the buffers (or arrays) are all full in circular arrays?
Answer: If the input-pointer is one less than the output-pointer in mod arithmetic.

4.21 How do you determine if the buffers (or arrays) are all empty?
Answer: If the input-pointer equals output-pointer.

Chapter 5

CPU SCHEDULING

CPU scheduling is the basis of multiprogrammed operating systems. By switching the CPU among processes, the operating system can make the computer more productive. In this chapter, we introduce the basic scheduling concepts and discuss in great length CPU scheduling. FCFS, SJF, Round-Robin, Priority, and the other scheduling algorithms should be familiar to the students. This is their first exposure to the idea of resource allocation and scheduling, so it is important that they understand how it is done. Gantt charts, simulations, and play acting are valuable ways to get the ideas across. Show how the ideas are used in other situations (like waiting in line at a post office, a waiter time sharing between customers, even classes being an interleaved round-robin scheduling of professors).

A simple project is to write several different CPU schedulers and compare their performance by simulation. The source of CPU and I/O bursts may be generated by random number generators or by a trace tape. The instructor can make the trace tape up in advance to provide the same data for all students. The file that I used was a set of jobs, each job being a variable number of alternating CPU and I/O bursts. The first line of a job was the word JOB and the job number. An alternating sequence of CPU *n* and I/O *n* lines followed, each specifying a burst time. The job was terminated by an END line with the job number again. Compare the time to process a set of jobs using FCFS, Shortest-Burst-Time, and Round-Robin scheduling. Round-Robin is more difficult, since it requires putting unfinished requests back in the ready queue.

The paper by Coffman and Kleinrock [1968a] is a good discussion of CPU scheduling for supplemental reading.

■ Answers to Exercises

5.1 A CPU scheduling algorithm determines an order for the execution of its scheduled processes. Given *n* processes to be scheduled on one processor, how many possible different schedules are there? Give a formula in terms of *n*.

Answer: $n!$ (n factorial = $n \times n - 1 \times n - 2 \times ... \times 2 \times 1$)

5.2 Define the difference between preemptive and nonpreemptive scheduling. State why strict nonpreemptive scheduling is unlikely to be used in a computer center.

Answer: Preemptive scheduling allows a process to be interrupted in the midst of its execution, taking the CPU away and allocating it to another process. Nonpreemptive scheduling ensures that a process relinquishes control of the CPU only when it finishes with its current CPU burst.

5.3 Consider the following set of processes, with the length of the CPU-burst time given in milliseconds:

Process	Burst Time	Priority
P_1	10	3
P_2	1	1
P_3	2	3
P_4	1	4
P_5	5	2

The processes are assumed to have arrived in the order P_1, P_2, P_3, P_4, P_5, all at time 0.

a. Draw four Gantt charts illustrating the execution of these processes using FCFS, SJF, a nonpreemptive priority (a smaller priority number implies a higher priority), and RR (quantum = 1) scheduling.

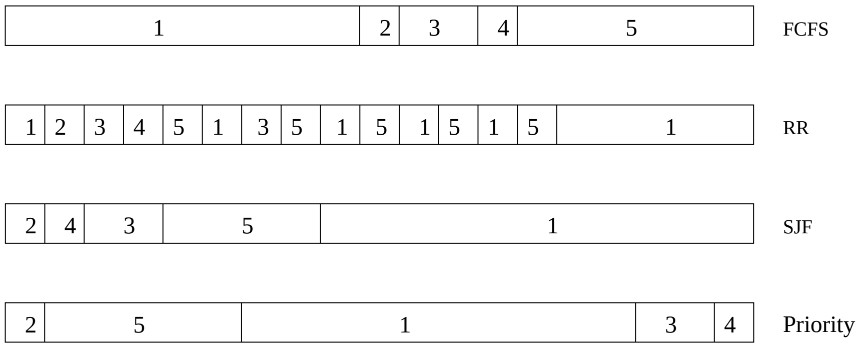
b. What is the turnaround time of each process for each of the scheduling algorithms in part a?

c. What is the waiting time of each process for each of the scheduling algorithms in part a?

d. Which of the schedules in part a results in the minimal average waiting time (over all processes)?

Answer:

a. The four Gantt charts are



b. Turnaround time

	FCFS	RR	SJF	Priority
P_1	10	19	19	16
P_2	11	2	1	1
P_3	13	7	4	18
P_4	14	4	2	19
P_5	19	14	9	6

c. Waiting time (turnaround time minus burst time)

	FCFS	RR	SJF	Priority
P_1	0	9	9	6
P_2	10	1	0	0
P_3	11	5	2	16
P_4	13	3	1	18
P_5	14	9	4	1

d. Shortest Job First

5.4 Suppose that the following processes arrive for execution at the times indicated. Each process will run the listed amount of time. In answering the questions, use nonpreemptive scheduling and base all decisions on the information you have at the time the decision must be made.

Process	Arrival Time	Burst Time
P_1	0.0	8
P_2	0.4	4
P_3	1.0	1

a. What is the average turnaround time for these processes with the FCFS scheduling algorithm?

b. What is the average turnaround time for these processes with the SJF scheduling algorithm?

c. The SJF algorithm is supposed to improve performance, but notice that we chose to run process P_1 at time 0 because we did not know that two shorter processes would arrive soon. Compute what the average turnaround time will be if the CPU is left idle for the first 1 unit and then SJF scheduling is used. Remember that processes P_1 and P_2 are waiting during this idle time, so their waiting time may increase. This algorithm could be known as future-knowledge scheduling.

Answer:

a. 10.53

b. 9.53

c. 6.86

Remember that turnaround time is finishing time minus arrival time, so you have to subtract the arrival times to compute the turnaround times. FCFS is 11 if you forget to subtract arrival time.

5.5 Consider a variant of the RR scheduling algorithm where the entries in the ready queue are pointers to the PCBs.

a. What would be the effect of putting two pointers to the same process in the ready queue?

b. What would be the major advantages and disadvantages of this scheme?

c. How would you modify the basic RR algorithm to achieve the same effect without the duplicate pointers?

Answer:

a. In effect, that process will have increased its priority since by getting time more often it is receiving preferential treatment.

b. The advantage is that more important jobs could be given more time, in other words, higher priority in treatment. The consequence, of course, is that shorter jobs will suffer.

c. Allot a longer amount of time to processes deserving higher priority, in other words, have two or more quantums possible in the round-robin scheme.

5.6 What advantage is there in having different time-quantum sizes on different levels of a multilevel queueing system?

Answer: Processes which need more frequent servicing, for instance interactive processes such as editors, can be in a queue with a small time quantum. Processes with no need for frequent servicing can be in a queue with a larger quantum, requiring fewer context switches to complete the processing, making more efficient use of the computer.

5.7 Consider the following preemptive priority-scheduling algorithm based on dynamically changing priorities. Larger priority numbers imply higher priority. When a process is waiting for the CPU (in the ready queue, but not running), its priority changes at a rate α; when it is running, its priority changes at a rate β. All processes are given a priority of 0 when they enter the ready queue. The parameters α and β can be set to give many different scheduling algorithms.

a. What is the algorithm that results from $\beta > \alpha > 0$?

b. What is the algorithm that results from $\alpha < \beta < 0$?

Answer:

a. FCFS

b. LIFO

5.8 Many CPU scheduling algorithms are parameterized. For example, the RR algorithm requires a parameter to indicate the time slice. Multilevel feedback queues require parameters to define the number of queues, the scheduling algorithms for each queue, the criteria used to move processes between queues, and so on.

These algorithms are thus really sets of algorithms (for example, the set of RR algorithms for all time slices, and so on). One set of algorithms may include another (for example, the FCFS algorithm is the RR algorithm with an infinite time quantum). What (if any) relation holds between the following pairs of sets of algorithms?

a. Priority and SJF

b. Multilevel feedback queues and FCFS

c. Priority and FCFS

d. RR and SJF

Answer:

a. The shortest job has the highest priority.

b. The lowest level of MLFQ is FCFS.

c. FCFS gives the highest priority to the job having been in existence the longest.

d. None

5.9 Suppose that a scheduling algorithm (at the level of short-term CPU scheduling) favors those processes that have used the least processor time in the recent past. Why will this algorithm favor I/O-bound programs and yet not permanently starve CPU-bound programs?
Answer: It will favor the I/O-bound programs because of the relatively short CPU burst request by them; however, the CPU-bound programs will not starve because the I/O-bound programs will relinquish the CPU relatively often to do their I/O.

5.10 Explain the differences in the degree to which the following scheduling algorithms discriminate in favor of short processes:

a. FCFS

b. RR

c. Multilevel feedback queues

Answer:

a. FCFS – discriminates against short jobs since any short jobs arriving after long jobs will have a longer waiting time.

b. RR – treats all jobs equally (giving them equal bursts of CPU time) so short jobs will be able to leave the system faster since they will finish first.

c. Multilevel feedback queues – work similar to the RR algorithm — they discriminate favorably toward short jobs.

■ Review Questions

5.1 What is a CPU burst? An I/O burst?
Answer:

- CPU burst: a time interval when a process uses CPU only.
- I/O burst: a time interval when a process uses I/O devices only.

5.2 An I/O-bound program would typically have what kind of CPU burst?
Answer: Short.

5.3 What is FIFO?
Answer: First-in-first-out queue.

5.4 What does "preemptive" mean?
Answer: Cause one process to temporarily halt, in order to run another.

5.5 What is the "dispatcher"?
Answer: Determines which processes are swapped out.

5.6 List performance criteria we could select to optimize our system.
Answer: CPU use, throughput, turnaround time, waiting time, response time.

5.7 We can take any one of the above criteria, and optimize it. List four ways we can optimize it.
Answer: Use average, minimum value, maximum value, minimum of variance.

5.8 What is throughput?
Answer: Number of jobs done per time period.

5.9 What is FCFS?
Answer: First-Come-First-Serve.

5.10 What is a Gantt chart? Explain how it is used.
Answer: A rectangle marked off horizontally in time units, marked off at end of each job or job-segment. It shows the distribution of time-bursts in time. It is used to determine total and average statistics on jobs processed, by formulating various scheduling algorithms on it.

5.11 What is the convoy effect?
Answer: Occurs when we have one CPU-bound job and many I/O-bound jobs. The I/O bound-jobs are lined up in a convoy, waiting for the CPU-bound job to finish up.

5.12 What is SJF?
Answer: Shortest job first. It usually means the job with the shortest CPU burst.

5.13 What are the advantages of SJF? Disadvantages?
Answer: Provably optimum in waiting time. But no way to know length of next CPU burst.

5.14 What is exponential averaging? How is it calculated?
Answer: A way of using previous history of a job to predict length of next CPU burst. $T(N+1) = A \times t(N) + (1 - A) \times T(N)$, where $t(N)$ is length of n^{th} CPU burst, and $T(N)$ is the previous average. A is the weight factor.

5.15 How are priority and SJF related?
Answer: Shortest jobs have highest priority.

5.16 List internally-derived priorities.
Answer: Time limits, memory usage, number of open files.

5.17 List externally-derived priorities.
Answer: Funding, politics, who, urgency.

5.18 What is indefinite blocking? How can it occur?
Answer: Also called starvation. A process with low priority that never gets a chance to execute. Can occur if CPU is continually busy with higher priority jobs.

5.19 What is "aging"?
Answer: Gradual increase of priority with age of job, to prevent "starvation."

5.20 What is SRTF (Shortest-Remaining-Time-First) scheduling?
Answer: A preemptive scheduling algorithm that gives high priority to a job with least amount of CPU burst left to complete.

5.21 What is round-robin scheduling?
Answer: Each job is given a time quantum slice to run; if not completely done by that time interval, job is suspended and another job is continued. After all other jobs have been given a quantum, first job gets its chance again.

5.22 True or False: Round-robin scheduling is preemptive.
Answer: True.

5.23 What is the time quantum used for?
Answer: Round-robin scheduling, to give each process the same processing time.

5.24 How should the time quantum be related to the context switch time?
Answer: Quantum should be very large compared to context switch time.

5.25 How should the time quantum be related to the CPU burst times?
Answer: 80% of CPU bursts should be shorter than time quantum.

5.26 Describe the foreground-background approach.
Answer: Low priority processes run in background; high priority jobs run in foreground; background runs only when foreground is empty, or waiting for I/O.

5.27 How can multilevel queues be scheduled? Which might have priority over others?
Answer:

a. Each queue can have absolute priority over lower queues.

b. Time-slice queues can, giving each queue a certain percent of time.

5.28 What are multilevel feedback queues?
Answer: Processes move from one queue to another, depending on changes in its conditions (that is, the CPU burst may change).

5.29 What is the "deterministic modeling" of text?
Answer: Sketching the Gantt chart for a given job set, and determining specified averages.

5.30 What are the advantages and disadvantages of deterministic modeling?
Answer:

- Advantages: simple to compute.
- Disadvantages: results apply only to the specified job set.

5.31 What is a trace tape?
Answer: A magnetic tape with record of actual jobs sets and times, created by monitoring a real system.

5.32 What are the advantages and disadvantages of using implementation to compare various scheduling algorithms?
Answer:

- Advantages: completely accurate.
- Disadvantages: cost in coding, cost in modifying operating system, cost in modifying data structures, bad reactions from users due to changing and comparing various scheduling schemes.

5.33 List two ways several computers can work together on sharing load.
Answer:

- One computer controls others.
- Each computer acts independently.

Chapter 6

PROCESS SYNCHRONIZATION

Chapter 6 is concerned with the topic of process synchronization among concurrently executing processes. Concurrency is generally very hard for students to deal with correctly, and so we have tried to introduce it and its problems with the classic process coordination problems: mutual exclusion, bounded-buffer, readers / writers, and so on. An understanding of these problems and their solutions is part of current operating system theory and development.

Additionally, students need to understand the effect that languages have on the way that we try to solve problems, and be familiar with critical regions and monitors.

Answers to Exercises

6.1 What is the meaning of the term *busy waiting*? What other kinds of waiting are there? Can busy waiting be avoided altogether? Explain your answer.

Answer:

- A process is waiting for an event to occur and it does so by executing instructions.
- A process is waiting for an event to occur in some waiting queue (e.g., I / O, semaphore) and it does so without having the CPU assigned to it.
- Busy waiting cannot be avoided altogether.

6.2 Prove that, in the bakery algorithm (Section 6.2.2), the following property holds: If P_i is in its critical section and P_k ($k \neq i$) has already chosen its $number[k] \neq 0$, then $(number[i],i) < (number[k],k)$.

Answer: No Answer

6.3 The first known correct software solution to the critical-section problem for two processes was developed by Dekker. The two processes, P_0 and P_1, share the following variables:

```
var flag: array [0..1] of boolean; (* initially false *)
    turn: 0..1;
```

```
repeat

    flag[i] := true;
    while flag[j]
        do if turn = j
            then begin
                    flag[i] := false;
                    while turn = j do no-op;
                    flag[i] := true;
                end;

    critical section

    turn := j;
    flag[i] := false;

    remainder section

until false;
```

Figure 6.24 The structure of process P_i in Dekker's algorithm.

The structure of process P_i (i = 0 or 1), with P_j (j = 1 or 0) being the other process, is shown in Figure 6.24.

Prove that the algorithm satisfies all three requirements for the critical-section problem.

Answer: To prove property (a) we note that each P_i enters its critical section only if *flag*[*j*] = *false*. Since only P_i can update *flag*[*j*], and since P_i inspects *flag*[*j*] only while *flag*[*i*] = *true*, the result follows.

a. To prove property (b), we first note that the value of the variable *turn* is changed only at the end of the critical section. Suppose that only process P_i wants to enter the critical section. In this case, it will find *flag*[*j*] = *false* and immediately enter the critical section, independent of the current value of *turn*. Suppose that both processes want to enter the critical section, and the value of *turn* = 0. Two cases are now possible. If P_i finds *flag*[0] = *false* then it will enter the critical section. If P_i finds *flag*[0] = *true* then we claim that P_0 will enter the critical section before P_1. Moreover, it will do so within a finite amount of time.

b. To demonstrate this fact, first consider process P_0. Since *turn* = 0, it will only be waiting for *flag*[1] to be set to *false*; more precisely, it will not be executing in the *begin* block associated with the *if* statement. Furthermore, it will not change the value of *flag*[0]. Meanwhile, process P_1 will find *flag*[0] = *true* and *turn* = 0. It will set *flag*[1] = *false* and wait until *turn* = 1. At this point, P_0 will enter its critical section. A symmetric argument can be made if *turn* = 1.

6.4 The first known correct software solution to the critical-section problem for *n* processes with a lower bound on waiting of $n - 1$ turns, was presented by Eisenberg and McGuire. The processes share the following variables:

```
var flag: array [0..n-1] of (idle, want-in, in-cs);
    turn: 0..n−1;
```

```
var j: 0..n;
repeat

    repeat
        flag[i] := want-in;
        j := turn;
        while j ≠ i
                then j := turn
                else j := j+1 mod n;
        flag[i] := in-cs;
        j := 0;
        while (j < n) and (j = i or flag[j] ≠ in-cs) do j := j+1;
    until (j ≥ n) and (turn = i or flag[turn] = idle);
    turn := i;

        critical section

    j := turn+1 mod n;
    while (flag[j] = idle) do j := j+1 mod n;
    turn := j;
    flag[i] := idle;

        remainder section

until false;
```

Figure 6.25 The structure of process P_i in Eisenberg and McGuire's algorithm.

All the elements of *flag* are initially *idle;* the initial value of *turn* is immaterial (between 0 and $n - 1$). The structure of process P_i is shown in Figure 6.25.

Prove that the algorithm satisfies all three requirements for the critical-section problem.

Answer: To prove that this algorithm is correct, we need to show that (1) mutual exclusion is preserved, (2) the progress requirement is satisfied, and (3) the bounded-waiting requirement is met.

To prove property (1), we note that each P_i enters its critical section only if *flag*[*j*] ≠ *in-cs* for all $j \neq i$. Since only P_i can set *flag*[*i*] = *in-cs,* and since P_i inspects *flag*[*j*] only while *flag*[*i*] = *in-cs,* the result follows.

To prove property (2), we observe that the value of *turn* can be modified only when a process enters its critical section and when it leaves its critical section. Thus, if no process is executing or leaving its critical section, the value of *turn* remains constant. The first contending process in the cyclic ordering (*turn*, *turn*+1, ..., *n*-1, 0, ..., *turn*-1) will enter the critical section.

To prove property (3) we observe that, when a process leaves the critical section, it must designate as its unique successor the first contending process in the cyclic ordering *turn* + 1, ..., *n* - 1, 0, ..., *turn* - 1, *turn*, ensuring that any process wanting to enter its critical section will do so within *n* - 1 turns.

6.5 In Section 6.3, we mentioned that disabling interrupts frequently could affect the system's clock. Explain why it could, and how such effects could be minimized.

Answer: Timekeeping is usually based on interrupts generated by a clock crystal. After a fixed number of oscillations, which equal the passage of an amount of time, an interrupt occurs and the computer increases its stored time. If interrupts are disabled, these clock ticks can be lost, and the time value is not incremented.

6.6 Show that, if the *wait* and *signal* operations are not executed atomically, then mutual exclusion may be violated.

Answer: Suppose the value of semaphore $S = 1$ and processes P_1 and P_2 execute *wait*(S) concurrently.

a. T_0: P_1 determines that value of $S = 1$

b. T_1: P_2 determines that value of $S = 1$

c. T_2: P_1 decrements S by 1 and enters critical section

d. T_3: P_3 decrements S by 1 and enters critical section

6.7 *The Sleeping-Barber Problem*. A barbershop consists of a waiting room with *n* chairs, and the barber room containing the barber chair. If there are no customers to be served, the barber goes to sleep. If a customer enters the barbershop and all chairs are occupied, then the customer leaves the shop. If the barber is busy, but chairs are available, then the customer sits in one of the free chairs. If the barber is asleep, the customer wakes up the barber. Write a program to coordinate the barber and the customers.

Answer: No Answer

6.8 *The Cigarette-Smokers Problem*. Consider a system with three *smoker* processes and one *agent* process. Each smoker continuously rolls a cigarette and then smokes it. But to roll and smoke a cigarette, the smoker needs three ingredients: tobacco, paper, and matches. One of the smoker processes has paper, another has tobacco, and the third has matches. The agent has an infinite supply of all three materials. The agent places two of the ingredients on the table. The smoker who has the remaining ingredient then makes and smokes a cigarette, signaling the agent on completion. The agent then puts out another two of the three ingredients, and the cycle repeats. Write a program to synchronize the agent and the smokers.

Answer: The shared data structures are

```
var a: array [0...2] of semaphore {initially = 0}
agent: semaphore {initially = 1}
```

The agent process code is as follows:

```
rep
repeat
    Set i, j to a value between 0 and 2.
    wait(agent);
    signal(a[i]);
    signal(a[j]);
until false;
```

Each smoker process needs two ingredients represented by integers *r* and *s* each with value between 0 and 2.

```
rep
repeat
    wait(a[r]);
    wait(a[s]);
    “smoke”
    signal(agent);
until false;
```

6.9 Demonstrate that monitors, conditional critical regions, and semaphores are all equivalent, insofar as the same types of synchronization problems can be implemented with them.

Answer: The following construct that transforms the *wait* and *signal* operations on a semaphore *S* into equivalent critical regions, proves that semaphores are as powerful as critical regions. A semaphore *S* is represented as a shared integer;

```
var S: shared integer;
```

The *wait*(*S*) and *signal*(*S*) operations are implemented as follows:

```
wait(S): region S when $S > 0$ do $S := S - 1$;
signal(S): region S do $S := S + 1$;
```

The implementation of critical regions in terms of semaphores in Section 6.6 proves that critical regions are as powerful as semaphores. The implementation of semaphores in terms of monitors in Section 6.7 proves that semaphores are as powerful as monitors. The proof that monitors are as powerful as semaphores follows from the following construct:

```
type semaphore = monitor
var busy: boolean;
    nonbusy: condition;

procedure entry wait;
    begin
        if busy then nonbusy.wait;
        busy := true;
    end;

procedure entry signal;
    begin
        busy := false;
        nonbusy.signal;
    end;

begin
    busy := false;
end.
```

6.10 Write a bounded-buffer monitor in which the buffers (portions) are embedded within the monitor itself.

Answer: No Answer

6.11 The strict mutual exclusion within a monitor makes the bounded-buffer monitor of Exercise 6.10 mainly suitable for small portions.

a. Explain why this assertion is true.

b. Design a new scheme that is suitable for larger portions.

Answer:

a. If the portions are large, then adding and removing data to the shared pool requires a considerable amount of time. Since the producer and consumer cannot execute in the monitor concurrently, parallelism is lost.

b. No Answer

6.12 Suppose that the *signal* statement can appear as only the last statement in a monitor procedure. Suggest how the implementation described in Section 6.7 can be simplified.

Answer: Since the signal statement can only appear as the last statement in a monitor procedure, the signaling process can exit the monitor immediately after executing the signal statement. Thus, there is no need for the semaphore *next* and the integer variable *next-count*.

- Each external procedure *F* will be replaced by

```
wait(mutex)
    body of F
signal(mutex)
```

- The operation *x.wait* can be implemented as

```
x-count := x-count + 1;
signal(mutex);
wait(x-sem);
x-count := x-count − 1;
```

- The operation *x.signal* can be implemented as

```
if x-count > 0
  then begin
           signal(x-sem);
           exit monitor
       end
  else signal(mutex)
```

6.13 Consider a system consisting of processes P_1, P_2, ..., P_n, each of which has a unique priority number. Write a monitor that allocates three identical line printers to these processes, using the priority numbers for deciding the order of allocation.

Answer: The monitor code is

```
type resource = monitor
var P: array[0..2] of boolean;
X: condition;
procedure acquire (id: integer, printer-id: integer);
   begin
         if P[0] and P[1] and P[2] then X.wait(id)
         if not P[0] then printer-id := 0;
            else if not P[1] then printer-id := 1;
                  else printer-id := 2;
         P[printer-id] := true;
   end

procedure release (printer-id: integer)
   begin
         P[printer-id] := false;
         X.signal;
   end

begin
   P[0] := P[1] := P[2] := false;
end
```

6.14 A file is to be shared among different processes, each of which has a unique number. The file can be accessed simultaneously by several processes, subject to the following constraint: The sum of all unique numbers associated with all the processes currently accessing the file must be less than *n*. Write a monitor to coordinate access to the file.

Answer: The monitor code is

```
type coordinator = monitor
var count: integer
S: condition

procedure acquire(id: integer);
   begin
         while(count + id $\geq$ n) do S.wait(id);
         count := count + id;
   end

procedure leave(id: integer);
   begin
         count := count − id;
         S.signal;
   end
begin
   count := 0;
end
```

6.15 Suppose that we replace the *wait* and *signal* operations of monitors with a single construct *await*(*B*), where *B* is a general Boolean expression that causes the process executing it to wait until *B* becomes true.

a. Write a monitor using this scheme to implement the readers–writers problem.

b. Explain why, in general, this construct cannot be implemented efficiently.

c. What restrictions need to be put on the *await* statement so that it can be implemented efficiently? (Hint: Restrict the generality of *B*; see Kessels [1977].)

Answer:

a. The monitor code is

```
type reader-writer = class
var v: record
            nreaders, nwriters: integer;
            busy: boolean;
        end;

procedure entry open-read;
        begin
            await(nwriters = 0);
            nreaders := nreaders + 1;
        end;

procedure entry close-read;
        begin
            nreaders := nreaders − 1;
        end;

procedure entry open-write;
        begin
            nwriters := nwriters + 1;
            await((not busy) and (nreaders = 0));
            busy := true;
        end;

procedure entry close-write;
        begin
            nwriters := nwriters − 1;
            busy := false;
        end;

  begin
      busy := false;
      nreaders := 0;
      nwriters := 0;
  end.
```

b. If the boolean expression includes formal parameters or local variables, then the evaluation of *B* for reactivation requires process switching, which is very expensive.

c. Allow *B* to include only global variables.

6.16 Write a monitor that implements an *alarm clock* that enables a calling program to delay itself for a specified number of time units (*ticks*). You may assume the existence of a real hardware clock, which invokes a procedure *tick* in your monitor at regular intervals.

Answer:

```
type alarm = monitor
var X: condition;

procedure delay (T: integer);
   begin
      X.wait (T);
      X.signal;
   end

procedure tick;
   begin
      X.signal
   end
```

6.17 Why does Solaris 2 implement multiple locking mechanisms? Under what circumstances does it use spinlocks, blocking semaphores, conditional variables, and readers–writers locks? Why does it use each mechanism?

Answer: Different locks are useful under different circumstances. Rather than make do with one type of lock which does not fit every lock situation (by adding code around the lock, for instance) it makes sense to include a set of lock types. Spinlocks are the basic mechanism used when a lock will be released in a short amount of time. If the lock is held by a thread which is not currently on a processor, then it becomes a blocking semaphore. Condition variables are used to lock longer code sections, because they are more expensive to initiate and release, but more efficient while they are held. Readers-writers locks are used on code which is used frequently, but mostly in a read-only fashion. Efficiency is increased by allowing multiple readers at the same time, but locking out everyone but a writer when a change of data is needed.

6.18 Explain the differences, in terms of cost, among the three storage types: volatile, nonvolatile, and stable.

Answer: Volatile storage is storage which fails when there is a power failure. Cache, main memory, and registers require a steady power source; when the system crashes and this source is interrupted, this type of memory is lost. Nonvolatile storage is storage which retains its content despite power failures. For example, disk and magnetic tape survive anything other than demagnetization or hardware/head crashes (and less likely things such as immersion in water, fire, etc.). Stable storage is storage which theoretically survives any type of failure. This type of storage can only be approximated with duplication.

6.19 Explain the purpose of the checkpoint mechanism. How often should checkpoints be performed? How does the frequency of checkpoints affect:

- System performance when no failure occurs?
- The time it takes to recover from a system crash?
- The time it takes to recover from a disk crash?

Answer: Checkpointing is done with log-based recovery schemes to reduce the amount of searching that needs to be done after a crash. If there is no checkpointing, then the entire log must be searched after a crash, and all transactions "redone" from the log. If checkpointing is used, then most of the log can be discarded. Since checkpoints are very expensive, how often they should be taken depends upon how reliable the system is. The more reliable the system, the less often a checkpoint should be taken.

6.20 Explain the concept of transaction atomicity.

Answer: A transaction is a sequence of instructions which, when executed as an atomic unit, takes the database from a consistent state to a consistent state.

6.21 Show that the two-phase locking protocol ensures conflict serializability.

Answer: Suppose two-phase locking does not ensure serializability. Then there exists a sequence of transactions T_0, T_1 ... T_{n-1} which obey 2PL and which produce a nonserializable schedule. We shall show that any nonserializable schedule is not 2PL. Without loss of generality, assume the following cycle exists: $T_0 \rightarrow T_1 \rightarrow T_2 \rightarrow ... \rightarrow T_n \rightarrow T_0$. Let α be the time that T_i releases its first lock. Then for all transactions such that $T_i \rightarrow T_j$, $\alpha_i < \alpha_j$. Then for the cycle we have

$$\alpha_0 < \alpha_1 < \alpha_2 < ... < \alpha_n < \alpha_0$$

Since $\alpha_0 < \alpha_0$ is a contradiction, no such cycle can exist.

6.22 Show that there are schedules that are possible under the two-phase locking protocol but are not possible under the timestamp protocol, and vice versa.

Answer:

- A schedule which is allowed in the two-phase locking protocol but not in the timestamp protocol is:

step	T_0	T_1	Precedence remarks
1	**lock-S**(A)		
2	**read**(A)		
3		**lock-X**(B)	
4		**write**(B)	
5		**unlock**(B)	
6	**lock-S**(B)		
7	**read**(B)		$T_1 \rightarrow T_0$
8	**unlock**(A)		
9	**unlock**(B)		

This schedule is not allowed in the timestamp protocol because at step 7, the W-timestamp of B is 1.

- A schedule which is allowed in the timestamp protocol but not in the two-phase locking protocol is:

step	T_0	T_1	T_2
1	**write**(A)		
2		**write**(A)	
3			**write**(A)
4	**write**(B)		
5		**write**(B)	

This schedule cannot have lock instructions added to make it legal under two-phase locking protocol because T_1 must unlock (A) between steps 2 and 3, and must lock (B) between steps 4 and 5.

■ Review Questions

6.1 What is a critical section?
Answer: A section of code that only one process at a time can be executing.

6.2 What is the critical-section problem?
Answer: To design an algorithm that allows at most one process into the critical section at a time, without deadlock.

6.3 Why have critical sections of programs, as defined by authors?
Answer: To allow no more than one process in at a time.

6.4 List the constraints Dijkstra placed on solutions to the critical-section problem.
Answer:

a. Simultaneous execution is equivalent to sequential execution in unknown order.

b. Speeds of the processes are independent of each other.

c. A process in noncritical section can't prevent other processes from entering the critical section.

d. Selection of admitting one process into critical section can't be indefinitely postponed.

6.5 What three requirements must a solution to the critical-section problem satisfy?
Answer: Mutual exclusion, progress, bounded waiting.

6.6 What variable is common between the two processes in algorithm 1?
Answer: *turn*. Note that *i* and *j* are not variables.

6.7 What is wrong with algorithm 1?
Answer: Since algorithm 1 requires strict alternation of processes in the execution of the critical section it does not satisfy the progress requirement.

6.8 What variable(s) is / are common between the two processes in algorithm 2?
Answer: A two-element boolean *flag* array.

6.9 What is wrong with algorithm 2? How do you prove it?
Answer: Violates the progress requirement (see page 168).

6.10 What variables are used in algorithm 3, which are common to both processes?
Answer: A two-element boolean array *flag* and *turn*.

6.11 What does execute "atomically" mean?
Answer: Executed as a group, with no context switches possible until all of the statements in the group are completed.

6.12 Define the wait-(postpone) operation, *wait*(S).
Answer: While semaphore is nonpositive, wait; when semaphore becomes positive, subtract one and exit.

6.13 Define the wakeup operation *signal*(S).
Answer: Add 1 to the semaphore.

6.14 Suppose we want to execute the statements S_1, S_2, and S_3 in sequence, but that S_2 has to be executed exclusively for one process at a time. Write the code needed using semaphores.
Answer: Assume Q = 1 initially. S_1; *wait*(Q); S_2; *signal*(Q); S_3.

6.15 Describe the Dining Philosophers problem.

Answer: Five philosophers around a table can either eat or think; they share five chopsticks; but each needs two to eat. The problem is to design an algorithm so that there is no deadlock or starvation.

Chapter 7

DEADLOCKS

Deadlock is a problem that can only arise in a system with multiple active asynchronous processes. It is important that the students learn the three basic approaches to deadlock: prevention, avoidance, and detection (although the terms *prevention* and *avoidance* are easy to confuse).

It can be useful to pose a deadlock problem in human terms and ask why human systems never deadlock. Can the students transfer this understanding of human systems to computer systems?

Projects can involve simulation: create a list of jobs consisting of requests and releases of resources (single type or multiple types). Ask the students to allocate the resources to prevent deadlock. This basically involves programming the Banker's Algorithm.

The survey paper by Coffman, Elphick, and Shoshani [1971] is good supplemental reading, but you might also consider having the students go back to the papers by Havender [1968], Habermann [1969], and Holt [1971a]. The last two were published in *CACM* and so should be readily available.

■ Answers to Exercises

7.1 List three examples of deadlocks that are not related to a computer-system environment.
Answer:

- Two cars crossing a single lane bridge from opposite directions.
- A person going down a ladder while another person is climbing up the ladder.
- Two trains traveling toward each other on the same track.

7.2 Is it possible to have a deadlock involving only one single process? Explain your answer.
Answer: No. This follows directly from the hold-and-wait condition.

7.3 People have said that proper spooling would eliminate deadlocks. Certainly, it eliminates from contention card readers, plotters, printers, and so on. It is even possible to spool tapes (called *staging* them), which would leave the resources of CPU time, memory, and disk space. Is it possible to have a deadlock involving these resources? If it is, how could such a deadlock occur? If it is not, why not? What deadlock scheme would seem best to eliminate these deadlocks (if any are possible), or what condition is violated (if they are not possible)?

Answer: It is possible to still have a deadlock. Process P_1 holds memory pages that are required by process P_2 , while P_2 is holding the CPU that is required by P_1. The best way to eliminate these types of deadlock is to use preemption.

7.4 Consider the traffic deadlock depicted in Figure 7.8.

a. Show that the four necessary conditions for deadlock indeed hold in this example.

b. State a simple rule that will avoid deadlocks in this system.

Answer:

a. Each section of the street is considered a resource.
   - **Mutual-exclusion** — only one vehicle on a section of the street.
   - **Hold-and-wait** — each vehicle is occupying a section of the street and is waiting to move to the next section.
   - **No-preemption** — a section of a street that is occupied by a vehicle cannot be taken away from the vehicle unless the car moves to the next section.
   - **Circular-wait** — each vehicle is waiting for the next vehicle in front of it to move.

b. Allow a vehicle to cross an intersection only if it is assured that the vehicle will not have to stop at the intersection.

7.5 Suppose that a system is in an unsafe state. Show that it is possible for the processes to complete their execution without entering a deadlock state.

Answer: Consider the following snapshot of the system.

	Allocation	*Max*	*Available*
	A B C D	*A B C D*	*A B C D*
P_0	0 0 1 2	0 0 1 2	1 5 2 0
P_1	1 0 0 0	1 7 5 0	
P_2	1 3 5 4	2 3 5 6	
P_3	0 6 3 2	0 6 5 2	
P_4	0 0 1 4	0 6 5 6	

By allowing P_1 to finish and return its resources to the *Available* list, we can then service the request of P_3. When P_3 returns its resources, *Available* contains (2 8 8 6), thus allowing all of the rest of the processes to finish in any order.

7.6 In a real computer system, neither the resources available nor the demands of processes for resources are consistent over long periods (months). Resources break or are replaced, new processes come and go, new resources are bought and added to the system. If deadlock is controlled by the banker's algorithm, which of the following changes can be made safely (without introducing the possibility of deadlock), and under what circumstances?

a. Increase *Available* (new resources added).

b. Decrease *Available* (resource permanently removed from system).

c. Increase *Max* for one process (the process needs more resources than allowed, it may want more).

d. Decrease *Max* for one process (the process decides it does not need that many resources).

e. Increase the number of processes.

f. Decrease the number of processes.

Answer:

a. Anytime

b. Only if *Max* demand of each process does not exceed total number of available resources, and the system remains in a safe state.

c. Same as (b)

d. Anytime

e. Anytime

f. Anytime

7.7 Prove that the safety algorithm presented in Section 7.5.3 requires an order of $m \times n^2$ operations.

Answer: Step 2 may be executed $n + (n - 1) + (n - 2) + ... + 3 + 2 + 1 = n \times (n + 1)/2$ times. In each iteration, m resource types must be examined. Therefore the algorithm requires $m \times n \times (n + 1)/2$ steps.

7.8 Consider a system consisting of four resources of the same type that are shared by three processes, each of which needs at most two resources. Show that the system is deadlock-free.

Answer: Suppose the system is deadlocked. This implies that each process is holding one resource and is waiting for one more. Since there are three processes and four resources, one process must be able to obtain two resources. This process requires no more resources and therefore it will return its resources when done.

7.9 Consider a system consisting of m resources of the same type, being shared by n processes. Resources can be requested and released by processes only one at a time. Show that the system is deadlock free if the following two conditions hold:

a. The maximum need of each process is between 1 and m resources.

b. The sum of all maximum needs is less than $m + n$.

Answer: Using the terminology of Section 7.6.2 we have:

a. $\sum_{i=1}^{n} Max_i < m + n$

b. $Max_i \geq 1$ for all i
Proof: $Need_i = Max_i - Allocation_i$
If there exists a deadlock state then:

c. $\sum_{i=1}^{n} Allocation_i = m$

Use a. to get: $\sum Need_i + \sum Allocation_i = \sum Max_i < m + n$
Use c. to get: $\sum Need_i + m < m + n$
Rewrite to get: $\sum_{i=1}^{n} Need_i < n$

This implies that there exists a process P_i such that $Need_i = 0$. Since $Max_i \geq 1$ it follows that P_i has at least one resource that it can release. Hence the system cannot be in a deadlock state.

7.10 Consider a computer system that runs 5000 jobs per month with no deadlock-prevention or deadlock-avoidance scheme. Deadlocks occur about twice per month, and the operator must terminate and rerun about 10 jobs per deadlock. Each job is worth about \$2 (in CPU time), and the jobs terminated tend to be about half-done when they are aborted.

A systems programmer has estimated that a deadlock-avoidance algorithm (such as the banker's algorithm) could be installed in the system with an increase in the average execution time per job of about 10 percent. Since the machine currently has 30-percent idle time, all 5000 jobs per month could still be run, although turnaround time would increase by about 20 percent on average.

a. What are the arguments for installing the deadlock-avoidance algorithm?

b. What are the arguments against installing the deadlock-avoidance algorithm?

Answer:

a. In order to effectively determine whether or not a deadlock has occurred in this particular environment it is necessary to install either a deadlock prevention or avoidance scheme. By installing the deadlock avoidance algorithm, the variance in average waiting time would be reduced.

b. If there is little priority placed on minimizing waiting time variance, then not installing this scheme would mean a reduction in constant cost.

7.11 We can obtain the banker's algorithm for a single resource type from the general banker's algorithm simply by reducing the dimensionality of the various arrays by 1. Show through an example that the multiple-resource-type banker's scheme cannot be implemented by individual application of the single-resource-type scheme to each resource type.

Answer: Consider a system with resource types A, B, C and 2 processes P_0, P_1 and the following snapshot of the system.

	Allocation	*Max*	*Need*	*Available*
P_0	1 2 2	2 3 4	1 1 2	1 1 1
P_1	1 1 2	2 3 3	1 2 1	

The system is not in a safe state. However, if we apply the single resource type banker's algorithm to each resource type individually we get the following:

- the sequence $< P_0, P_1 >$ satisfies the safety requirement for resource A
- the sequence $< P_0, P_1 >$ satisfies the safety requirement for resource B
- the sequence $< P_1, P_0 >$ satisfies the safety requirement for resource C

and thus the system should be in a safe state.

7.12 Can a system detect that some of its processes are starving? If you answer "yes," explain how it can. If you answer "no," explain how the system can deal with the starvation problem.

Answer: Detection of starvation in effect requires future knowledge since no amount of record-keeping statistics on processes can determine if it is making "progress" or not. However, starvation can be prevented by "aging" a process. This means maintaining a rollback count for each process, and including this as part of the cost factor in the selection process for a victim for preemption / rollback.

7.13 Consider the following snapshot of a system:

	Allocation	*Max*	*Available*
	A B C D	*A B C D*	*A B C D*
P_0	0 0 1 2	0 0 1 2	1 5 2 0
P_1	1 0 0 0	1 7 5 0	
P_2	1 3 5 4	2 3 5 6	
P_3	0 6 3 2	0 6 5 2	
P_4	0 0 1 4	0 6 5 6	

Answer the following questions using the banker's algorithm:

a. What is the content of the matrix *Need*?

b. Is the system in a safe state?

c. If a request from process P_1 arrives for (0,4,2,0), can the request be granted immediately?

Answer:

a. Since *Need* = *Max* − *Allocation*, the content of *Need* is

A B C D
0 0 0 0
0 7 5 0
1 0 0 2
0 0 2 0
0 6 4 2

b. Yes, the sequence $<P_0, P_2, P_1, P_3, P_4>$ satisfies the safety requirement.

c. Yes. Since
   i. $(0,4,2,0) \leq Available = (1,5,2,0)$
   ii. $(0,4,2,0) \leq Max_i = (1,7,5,0)$
   iii. The new system state after the allocation is made is

	Allocation	*Max*	*Need*	*Available*
P_0	0 0 1 2	0 0 1 2	0 0 0 0	1 1 0 0
P_1	1 4 2 0	1 7 5 0	0 3 3 0	
P_2	1 3 5 4	2 3 5 6	1 0 0 2	
P_3	0 6 3 2	0 6 5 2	0 0 2 0	
P_4	0 0 1 4	0 6 5 6	0 6 4 2	

and the sequence $< P_0, P_2, P_1, P_3, P_4 >$ satisfies the safety requirement.

7.14 Consider the following resource-allocation policy. Requests and releases for resources are allowed at any time. If a request for resources cannot be satisfied because the resources are not available, then we check any processes that are blocked, waiting for resources. If they have the desired resources, then these resources are taken away from them and are given to the requesting process. The vector of resources for which the waiting process is waiting is increased to include the resources that were taken away.

For example, consider a system with three resource types and the vector *Available* initialized to (4,2,2). If process P_0 asks for (2,2,1), it gets them. If P_1 asks for (1,0,1), it gets them. Then, if P_0 asks for (0,0,1), it is blocked (resource not available). If P_2 now asks for (2,0,0), it gets the available one (1,0,0) and one that was allocated to P_0 (since P_0 is blocked). P_0's *Allocation* vector goes down to (1,2,1), and its *Need* vector goes up to (1,0,1).

a. Can deadlock occur? If so, give an example. If not, which necessary condition cannot occur?

b. Can indefinite blocking occur?

Answer:

a. Deadlock cannot occur because preemption exists.

b. Yes. A process may never acquire all the resources it needs if they are continuously preempted by a series of requests such as those of process *C*.

7.15 Suppose that you have coded the deadlock-avoidance safety algorithm and now have been asked to implement the deadlock-detection algorithm. Can you do so by simply using the safety algorithm code and redefining $Max_i = Waiting_i + Allocation_i$, where $Waiting_i$ is a vector specifying the resources process i is waiting for, and $Allocation_i$ is as defined in Section 7.5? Explain your answer.

Answer: By redefining *Max* in the safety algorithm, we also redefine *Need*(i) = *waiting*(i). Now *Need* is the same as *Request* in the deadlock-detection algorithm, and the algorithms are equivalent.

■ Review Questions

7.1 List types of resources we might consider in deadlock problems on computers.
Answer: CPU cycles, memory space, files, I/O devices, tape drives, printers.

7.2 Define deadlock.
Answer: A situation where every process is waiting for an event that can be triggered only by another process.

7.3 What are the four necessary conditions needed before deadlock can occur?
Answer:

a. At least one resource must be held in a nonsharable mode.

b. A process holding at least one resource is waiting for more resources held by other processes.

c. Resources cannot be preempted.

d. There must be a circular waiting.

7.4 What is a system resource-allocation graph (SRAG) in general?
Answer: A graph which shows the resources and processes, and the relationships among them.

7.5 How is a request indicated in a SRAG?
Answer: A line directed from the process to the resource box.

7.6 How is an allocation indicated in a SRAG?
Answer: A line from a resource in a box to the process.

7.7 True/False: In an SRAG, if there are no cycles, then no deadlock exists.
Answer: True.

7.8 True/False: In an SRAG, if there are cycles, then deadlock exists.
Answer: False; a deadlock *may* exist.

7.9 List three overall strategies in handling deadlocks.
Answer:

a. Ensure system will never enter a deadlock state.

b. Allow deadlocks, but devise schemes to recover from them.

c. Pretend deadlocks don't happen.

7.10 Give examples of sharable resources.
Answer: Read-only files, shared programs and libraries.

7.11 Give examples of nonsharable resources.
Answer: Printer, magnetic tape drive, update-files, card readers.

7.12 Can we break the first condition for deadlock to prevent deadlock?
Answer: Usually not possible. But if done, you may risk privacy and integrity of your data.

7.13 List two ways we can break the second condition to prevent deadlock.
Answer:

a. Process is allocated all resources it needs before starting.

b. Process receives resources only if it has none.

7.14 List two ways we can break the third condition to prevent deadlock.
Answer:

a. Requesting process is preempted of its current resources.

b. Requesting process preempts resources from other processes.

7.15 What do authors mean by imposing a total ordering on the resources?
Answer: Each resource is assigned a unique number such that resources needed typically by processes early are given low numbers, and resources needed later are given higher numbers.

7.16 List two ways we can break the fourth condition to prevent deadlock, using resource ordering.
Answer:

a. Let processes request only resources with higher numbers.

b. If a process requests a resource, it must release resources that have lower numbers.

7.17 To avoid deadlock, what information do we need on the current processes?
Answer: Simplest scheme: each process declares the maximum number of resources it may need.

7.18 What is a safe state?
Answer: A set of resource allocations such that the system can allocate resources to each process (up to its max) in some order, and still avoid a deadlock.

7.19 What is a claim edge?
Answer: A dashed line from process to resource, indicating potential request of resource by the process.

7.20 List the data structures needed for the banker's algorithm.
Answer:

- available vector *Available*(m)
- demand matrix *Max*(n,m)
- allocation matrix *Allocation*(n,m)
- need matrix *Need*(n,m)

7.21 Summarize the banker's algorithm.
Answer:

a. If request for process *i* exceeds its need, error has occurred.

b. If request of process *i* exceeds available resources, process *i* must wait.

c. The system temporarily allocates the resources process *i* wants; if the state is unsafe, the allocation is postponed.

7.22 Summarize the Safety Algorithm.
Answer:

a. Initialize vector *Work* to *Available* and set vector *Finish* to false.

b. Find a process such that *Finish*(*i*) = false and *Need*(*i*) *leq Work*.

c. If found, add *Allocation*(*i*) to *Work*(*i*), *Finish*(*i*) to true, and go to step b.

d. If not found, continue here. If *Finish*(*i*) = true for all processes then state is safe, else it is unsafe.

7.23 How can we determine whether current state is "safe" in systems with only one instance of each resource type?
Answer: State is unsafe if any cycle exists.

7.24 What does a wait-for graph show?
Answer: Shows which process is waiting for other process(es).

7.25 How do you create a wait-for graph out of a resource-allocation graph?
Answer: Delete resource nodes, and connect the remaining lines, head of one to tail of line previously at same node.

7.26 What conditions must exist before a wait-for graph is useful in detecting deadlocks?
Answer: A cycle.

7.27 What does a cycle in a wait-for graph indicate?
Answer: A deadlock.

7.28 List three options for breaking an existing deadlock.
Answer:

a. Violate mutual exclusion, risking data.

b. Abort a process.

c. Preempt resources of some process.

7.29 What three issues must be considered in the case of preemption?
Answer:

a. Select a victim to be preempted.

b. Determine how far back to rollback the victim.

c. Determine means for preventing that process from being "starved."

7.30 List some items involved in determining the cost of a rollback.
Answer:

a. Priority

b. Time left to complete process

c. Time already expended on process

d. Number and type of resources needed to remove deadlock

e. Number of procesees involved in the rollback

7.31 What is starvation?
Answer: System is not deadlocked, but at least one process is indefinitely postponed.

7.32 List four classes of resources, and the corresponding typical method of handling deadlock for each.
Answer:

a. Internal (PCBs): resource ordering

b. Central memory: preemption and swapping

c. Job resources: avoidance

d. Swappable space: preallocation

Chapter 8

MEMORY MANAGEMENT

Although many systems are demand paged (discussed in Chapter 9), there are still many that are not, and in many cases the simpler memory management strategies may be better, especially for small dedicated systems. We want the student to learn about all of them: resident monitor, swapping, partitions, paging, and segmentation.

The paper by Hoare and McKeag [1972] is very good, but unfortunately is quite long and hard to get. The papers by Kilburn et al. [1961, 1962] on Atlas and Lichtenberger and Pirtle [1965] on XDS-940 are also good background reading since they were early influential systems. The main problem with them is that they seem very, very dated.

Answers to Exercises

8.1 Explain the difference between logical and physical addresses.
Answer:

- Logical addresses are those generated by user programs relative to location 0 in memory.
- Physical addresses are the actual addresses used to fetch and store data in memory.

8.2 Explain the difference between internal and external fragmentation.
Answer: Internal fragmentation is the area in a region or a page that is not used by the job occupying that region or page. This space is unavailable for use by the system until that job is finished and the page or region is released.

8.3 Explain the following allocation algorithms:

a. First-fit

b. Best-fit

c. Worst-fit

Answer:

a. First-fit: search the list of available memory and allocate the first block that is big enough.

b. Best-fit: search the entire list of available memory and allocate the smallest block that is big enough.

c. Worst-fit: search the entire list of available memory and allocate the largest block. (The justification for this scheme is that the leftover block produced would be larger and potentially more useful than that produced by the best-fit approach.)

8.4 When a process is rolled out of memory, it loses its ability to use the CPU (at least for a while). Describe another situation where a process loses its ability to use the CPU, but where the process does not get rolled out.
Answer: When an interrupt occurs.

8.5 Given memory partitions of 100K, 500K, 200K, 300K, and 600K (in order), how would each of the First-fit, Best-fit, and Worst-fit algorithms place processes of 212K, 417K, 112K, and 426K (in order)? Which algorithm makes the most efficient use of memory?
Answer:

a. First-fit:

b. 212K is put in 500K partition

c. 417K is put in 600K partition

d. 112K is put in 288K partition (new partition 288K = 500K - 212K)

e. 426K must wait

f. Best-fit:

g. 212K is put in 300K partition

h. 417K is put in 500K partition

i. 112K is put in 200K partition

j. 426K is put in 600K partition

k. Worst-fit:

l. 212K is put in 600K partition

m. 417K is put in 500K partition

n. 112K is put in 388K partition

o. 426K must wait

In this example, Best-fit turns out to be the best.

8.6 Consider a system where a program can be separated into two parts: code and data. The CPU knows whether it wants an instruction (instruction fetch) or data (data fetch or store). Therefore, two base–limit register pairs are provided: one for instructions and one for data. The instruction base–limit register pair is automatically read-only, so programs can be shared among different users. Discuss the advantages and disadvantages of this scheme.
Answer: The major advantage of this scheme is that it is an effective mechanism for code and data sharing. For example, only one copy of an editor or a compiler needs to be kept in memory, and this code can be shared by all processes needing access to the editor or compiler code. Another advantage is protection of code against erroneous modification. The

only disadvantage is that the code and data must be separated, which is usually adhered to in a compiler generated code.

8.7 Why are page sizes always powers of 2?

Answer: Recall that paging is implemented by breaking up an address into a page and offset number. It is most efficient to break the address into X page bits and Y offset bits, rather than perform arithmetic on the address to calculate the page number and offset. Because each bit position represents a power of 2, splitting an address between bits results in a page size that is a power of 2.

8.8 Consider a logical address space of eight pages of 1024 words each, mapped onto a physical memory of 32 frames.

a. How many bits are there in the logical address?

b. How many bits are there in the physical address?

Answer:

a. Logical address: 13 bits

b. Physical address: 15 bits

8.9 Why is it that, on a system with paging, a process cannot access memory it does not own? How could the operating system allow access to other memory? Why should it or should it not?

Answer: An address on a paging system is a logical page number and an offset. The physical page is found by searching a table based on the logical page number to produce a physical page number. Because the operating system controls the contents of this table, it can limit a process to accessing only those physical pages allocated to the process. There is no way for a process to refer to a page it does not own because the page will not be in the page table. To allow such access, an operating system simply needs to allow entries for non-process memory to be added to the process' page table. This is useful when two or more processes need to exchange data — they just read and write to the same physical addresses (which may be at varying logical addresses). This makes for very efficient interprocess communication.

8.10 Consider a paging system with the page table stored in memory.

a. If a memory reference takes 200 nanoseconds, how long does a paged memory reference take?

b. If we add associative registers, and 75 percent of all page-table references are found in the associative registers, what is the effective memory reference time? (Assume that finding a page-table entry in the associative registers takes zero time, if the entry is there.)

Answer:

a. 400 nanoseconds; 200 nanoseconds to access the page table and 200 nanoseconds to access the word in memory.

b. Effective access time = $0.75 \times$ (200 nanoseconds) + $0.25 \times$ (400 nanoseconds) = 250 nanoseconds.

8.11 What is the effect of allowing two entries in a page table to point to the same page frame in memory? Explain how this effect could be used to decrease the amount of time needed to copy a large amount of memory from one place to another. What would the effect of updating some byte in the one page be on the other page?

Answer: By allowing two entries in a page table to point to the same page frame in memory, users can share code and data. If the code is reentrant, much memory space can be saved through the shared use of large programs such as text editors, compilers, database systems, etc. "Copying" large amounts of memory could be effected by having different page tables point to the same memory location.

However, sharing of nonreentrant code or data means that any user having access to the code can modify it and these modifications would be reflected in the other user's "copy."

8.12 Why are segmentation and paging sometimes combined into one scheme?

Answer: Segmentation and paging are often combined in order to improve upon each other. Segmented paging is helpful when the page table becomes very large. A large contiguous section of the page table that is unused can be collapsed into a single segment table entry with a page table address of zero. Paged segmentation handles the case of having very long segments that require a lot of time for allocation. By paging the segments, we reduce wasted memory due to external fragmentation as well as simplify the allocation.

8.13 Describe a mechanism by which one segment could belong to the address space of two different processes.

Answer: Since segment tables are a collection of base–limit registers, segments can be shared when entries in the segment table of two different jobs point to the same physical location. The two segment tables must have identical base pointers and the shared segment number must be the same in the two processes.

8.14 Explain why it is easier to share a reentrant module using segmentation than it is to do so when pure paging is used.

Answer: Since segmentation is based on a logical division of memory rather than a physical one, segments of any size can be shared with only one entry in the segment tables of each user. With paging there must be a common entry in the page tables for each page that is shared.

8.15 Sharing segments among processes without requiring the same segment number is possible in a dynamically linked segmentation system.

a. Define a system that allows static linking and sharing of segments without requiring that the segment numbers be the same.

b. Describe a paging scheme that allows pages to be shared without requiring that the page numbers be the same.

Answer: Both of these problems reduce to a program being able to reference both its own code and its data without knowing the segment or page number associated with the address. MULTICS solved this problem by associating four registers with each process. One register had the address of the current program segment, another had a base address for the stack, another had a base address for the global data, and so on. The idea is that all references have to be indirect through a register that maps to the current segment or page number. By changing these registers, the same code can execute for different processes without the same page or segment numbers.

8.16 Consider the following segment table:

Segment	Base	Length
0	219	600
1	2300	14
2	90	100
3	1327	580
4	1952	96

What are the physical addresses for the following logical addresses?

a. 0,430

b. 1,10

c. 2,500

d. 3,400

e. 4,112

Answer:

a. 219 + 430 = 649

b. 2300 + 10 = 2310

c. illegal reference, trap to operating system

d. 1327 + 400 = 1727

e. illegal reference, trap to operating system

8.17 Consider the Intel address translation scheme shown in Figure 8.28.

a. Describe all the steps that are taken by the Intel 80386 in translating a logical address into a physical address.

b. What are the advantages to the operating system of hardware that provides such complicated memory translation hardware?

c. Are there any disadvantages to this address translation system?

Answer:

a. The selector is an index into the segment descriptor table. The segment descriptor result plus the original offset is used to produce a linear address with a dir, page, and offset. The dir is an index into a page directory. The entry from the page directory selects the page table, and the page field is an index into the page table. The entry from the page table, plus the offset, is the physical address.

b. Such a page translation mechanism offers the flexibility to allow most operating systems to implement their memory scheme in hardware, instead of having to implement some parts in hardware and some in software. Because it can be done in hardware it is more efficient (and the kernel is simpler).

c. Address translation can take longer due to the multiple table lookups it can invoke. Caches help, but there will still be cache misses.

8.18 In the IBM/370, memory protection is provided through the use of *keys*. A key is a 4-bit quantity. Each 2K block of memory has a key (the storage key) associated with it. The CPU also has a key (the protection key) associated with it. A store operation is allowed only if both keys are equal, or if either is zero. Which of the following memory-management schemes could be used successfully with this hardware?

a. Bare machine

b. Single-user system

c. Multiprogramming with a fixed number of processes

d. Multiprogramming with a variable number of processes

e. Paging

f. Segmentation

Answer:

a. Protection not necessary, set system key to 0.

b. Set system key to 0 when in supervisor mode.

c. Region sizes must be fixed in increments of 2k bytes, allocate key with memory blocks.

d. Same as above.

e. Frame sizes must be in increments of 2k bytes, allocate key with pages.

f. Segment sizes must be in increments of 2k bytes, allocate key with segments.

■ Review Questions

8.1 What is binding?
Answer: Setting the actual addresses used by each nonrelocatable address of a program.

8.2 What are overlays?
Answer: Segments or sets of routines, A, which are loaded into the same area of memory as other routines, B; A and B are not in memory concurrently, but one erases the other when loaded in.

8.3 What is the disadvantage of using overlays?
Answer: Programmer must carefully design the program and data structures so that the overlays won't interfere with each other.

8.4 What is dynamic loading?
Answer: Loading a routine only when it is called and not yet in memory; the routine will not be loaded into memory until first time it is called.

8.5 What is the advantage of dynamic loading?
Answer: Routines that are never used are never loaded; thus more free memory.

8.6 What is a relocation register?
Answer: A base register used to give the lowest physical address for a process.

8.7 List two ways of fixing partitions into place.
Answer:

a. Using upper/lower bounds registers for current executing process.
b. Using a base register and a limit register.

8.8 List two ways to classify jobs by memory requirements.
Answer:

a. User submits memory requirements along with job.
b. System determines memory requirements.

8.9 List eight ways of scheduling jobs.
Answer:

a. Each queue separately.
b. All jobs in one queue.
c. Keep memory regions from being idle.
d. Place small job in big region, if that's the only one available.
e. Wait for small region to open up for a small job.
f. Allow swapping.
g. High-priority jobs first.
h. Allow swapping back into different region than swapped out.

8.10 What is swapping?
Answer: Copying a process from memory to disk to allow space for other processes.

8.11 List ways of reducing the context switch time.
Answer:

a. Minimize the amount of memory of a process to be swapped.

b. Increase the speed of the disk used for swapped-out processes.

c. Overlap swapping and program execution.

8.12 List three ways of treating jobs which request too much memory, once started in a given partition.
Answer:

a. Abort job with run-time message.

b. Return control to job; if it can't adjust to smaller memory, abort.

c. Swap job out.

8.13 What is the system manager's main problem in using fixed partitions?
Answer: Determining the optimum number of partitions and their size.

8.14 List the common allocation methods. Which is the poorest? What was the rationale for even considering it?
Answer:

a. First-fit.

b. Best-fit.

c. Worst-fit — poorest. Assumes that most jobs are about same size.

8.15 What is internal fragmentation?
Answer: Wasted space within a partition.

8.16 What is external fragmentation?
Answer: Wasted space due to empty partitions being too small for current processes.

8.17 What are variable partitions?
Answer: Partitions that can be moved in location, and can be changed in number.

8.18 What is compaction? Why use it?
Answer: Movement of processes to eliminate small partitions. It allows smaller partitions to form fewer larger ones, to allow larger processes to run.

8.19 What is paging?
Answer: Splitting program up into a group of fixed-equal-sized partitions, allowing the parts to be non-contiguous.

8.20 What is a frame?
Answer: Fixed-size block of physical memory, each block of same size as page.

8.21 What is contained in the page table?
Answer: Base address of each frame, and corresponding page number.

8.22 How are the page number and offset numbers obtained?
Answer: Logical address is split into two parts: right-hand bits give the offset numbers, and left-hand bits give the page number.

8.23 Describe the page-to-frame translation.
Answer: Logical address is split into page offset and page number. Scan page table for page number; corresponding entry is the frame number, which is combined with page offset to give physical address.

8.24 How many frames are needed for each page?
Answer: One.

8.25 How much fragmentation occurs with paging? Which type?
Answer: On the average, one-half of last page in each job; this is internal fragmentation.

8.26 In what order are the frames assigned?
Answer: In the order of the free-frame list.

8.27 List three ways of implementing the page table.
Answer:

a. Dedicated registers.

b. In main memory.

c. Associative registers (cache).

8.28 What is an associative register?
Answer: A register in which no search is needed to find a key; all parts are given a key at once; the part holding the key is the only part to respond.

8.29 List advantages of paging.
Answer:

a. Sharing common code.

b. Reducing fragmentation.

8.30 What are page protection bits?
Answer: Flag bits associated with each page to flag read / write or read-only.

8.31 What is reentrant code?
Answer: Code that can be used by several users simultaneously. It has no code that users can alter during execution.

8.32 How was memory mapping used in extending the usefulness of minicomputers?
Answer: Allowed increased memory space without changing the instruction set.

8.33 What table does the operating system use to keep track of frame allocations?
Answer: Frame table.

8.34 What is segmentation?
Answer: Breaking program up into its logical segments, and allocating space for these segments into memory separately. The segments may be of variable length, and need not be allocated contiguously.

8.35 What is the logical address space? Physical address space?
Answer:

a. Collection of segments or pages; each segment has a name and length, and is numbered. Each page is numbered, and has same length as any other, but is not named.

b. Actual memory regions.

8.36 In what ways is segmentation both like and unlike the variable size partition allocation scheme.
Answer:

a. Like: has partitions, external fragmentation.

b. Unlike: partitions are of different sizes.

8.37 What advantages does segmentation have over paging?
Answer:

a. Can associate protection with critical segments, without protecting other items.

b. Can share code and data with other users, tightly, so that only the desired portions are shared.

8.38 What problems arise in sharing code in segmentation schemes?
Answer: Shared code must have same segment number for each user; segmentation must allow for this.

8.39 How does fragmentation for segmentation differ from that in paging?
Answer: Same, except for segments being variable length.

8.40 Can paging and segmentation be combined in a single operating system? List two ways.
Answer:

a. Large pages, with segmentation within pages.

b. Large segments, with paging done within segments.

Chapter 9

VIRTUAL MEMORY

Virtual memory can be a very interesting subject since it has so many different aspects: page faults, managing the backing store, page replacement, frame allocation, thrashing, page size. The objectives of this chapter are to explain these concepts and show how paging works.

A simulation is probably the easiest way to allow the students to program several of the page replacement algorithms and see how they really work. If an interactive graphics display can be used to display the simulation as it works, the students may be better able to understand how paging works.

■ Answers to Exercises

9.1 When do page faults occur? Describe the actions taken by the operating system when a page fault occurs.

Answer: A page fault occurs when an access to a page that has not been brought into main memory takes place. The operating system verifies the memory access, aborting the program if it is invalid. If it is valid a free frame is located and I/O requested to read the needed page into the free frame. Upon completion of I/O, the process table and page table are updated and the instruction is restarted.

9.2 Assume a page reference string for a process with *m* frames (initially all empty). The page reference string has length *p* with *n* distinct page numbers occurring in it. For any page-replacement algorithms,

a. What is a lower bound on the number of page faults?

b. What is an upper bound on the number of page faults?

Answer:

a. *n*

b. *p*

9.3 A certain computer provides its users with a virtual-memory space of 2^{32} bytes. The computer has 2^{18} bytes of physical memory. The virtual memory is implemented by paging, and the page size is 4096 bytes. A user process generates the virtual address 11123456. Explain how the system establishes the corresponding physical location. Distinguish between software and hardware operations.
Answer: The virtual address in binary form is

0001 0001 0001 0010 0011 0100 0101 0110

Since the page size is 2^{12}, the page table size is 2^{20}. Therefore the low-order 12 bits "0100 0101 0110" are used as the displacement into the page, while the remaining 20 bits "0001 0001 0001 0010 0011" are used as the displacement in the page table.

9.4 Which of the following programming techniques and structures are "good" for a demand-paged environment ? Which are "not good"? Explain your answers.

a. Stack
b. Hashed symbol table
c. Sequential search
d. Binary search
e. Pure code
f. Vector operations
g. Indirection

Answer:

a. Stack — good.
b. Hashed symbol table — not good.
c. Sequential search — good.
d. Binary search — not good.
e. Pure code — good.
f. Vector operations — good.
g. Indirection — not good.

9.5 Suppose we have a demand-paged memory. The page table is held in registers. It takes 8 milliseconds to service a page fault if an empty page is available or the replaced page is not modified, and 20 milliseconds if the replaced page is modified. Memory access time is 100 nanoseconds.
Assume that the page to be replaced is modified 70 percent of the time. What is the maximum acceptable page-fault rate for an effective access time of no more than 200 nanoseconds?
Answer:

$$\begin{aligned}
0.2\ \mu\text{sec} &= (1 - P) \times 0.1\ \mu\text{sec} + (0.3P) \times 8 \text{ millisec} + (0.7P) \times 20 \text{ millisec} \\
0.1 &= -0.1P + 2400\ P + 14000\ P \\
0.1 &\simeq 16{,}400\ P \\
P &\simeq 0.000006
\end{aligned}$$

9.6 Consider the following page-replacement algorithms. Rank these algorithms on a five-point scale from “bad” to “perfect” according to their page-fault rate. Separate those algorithms that suffer from Belady’s anomaly from those that do not.

a. LRU replacement

b. FIFO replacement

c. Optimal replacement

d. Second-chance replacement

Answer:

Rank	Algorithm	Suffer from Belady’s anomaly
1	Optimal	no
2	LRU	no
3	Second-chance	yes
4	FIFO	yes

9.7 When virtual memory is implemented in a computing system, there are certain costs associated with the technique, and certain benefits. List the costs and the benefits. Is it possible for the costs to exceed the benefits? If it is, what measures can be taken to ensure that this does not happen?
Answer: The costs are additional hardware and slower access time. The benefits are good utilization of memory and larger logical address space than physical address space.

9.8 An operating system supports a paged virtual memory, using a central processor with a cycle time of 1 microsecond. It costs an additional 1 microsecond to access a page other than the current one. Pages have 1000 words, and the paging device is a drum that rotates at 3000 revolutions per minute, and transfers 1 million words per second. The following statistical measurements were obtained from the system:

- 1 percent of all instructions executed accessed a page other than the current page.
- Of the instructions that accessed another page, 80 percent accessed a page already in memory.
- When a new page was required, the replaced page was modified 50 percent of the time.

Calculate the effective instruction time on this system, assuming that the system is running one process only, and that the processor is idle during drum transfers.
Answer:

$$\begin{aligned}
\text{effective access time} &= 0.99 \times (1\ \mu\text{sec} + 0.008 \times (2\ \mu\text{sec}) \\
&\quad + 0.002 \times (10{,}000\ \mu\text{sec} + 1{,}000\ \mu\text{sec}) \\
&\quad + 0.001 \times (10{,}000\ \mu\text{sec} + 1{,}000\ \mu\text{sec}) \\
&= (0.99 + 0.016 + 22.0 + 11.0)\ \mu\text{sec} \\
&= 34.0\ \mu\text{sec}
\end{aligned}$$

9.9 Consider a demand-paging system with the following time-measured utilizations:

CPU utilization	20%
Paging disk	97.7%
Other I/O devices	5%

Which (if any) of the following will (probably) improve CPU utilization? Explain your answer.

a. Install a faster CPU.

b. Install a bigger paging disk.

c. Increase the degree of multiprogramming.

d. Decrease the degree of multiprogramming.

e. Install more main memory.

f. Install a faster hard disk, or multiple controllers with multiple hard disks.

g. Add prepaging to the page fetch algorithms.

h. Increase the page size.

Answer: The system obviously is spending most of its time paging, indicating over-allocation of memory. If the level of multiprogramming is reduced resident processes would page fault less frequently and the CPU utilization would improve. Another way to improve performance would be to get more physical memory or a faster paging drum.

a. Get a faster CPU — No.

b. Get a bigger paging drum — No.

c. Increase the degree of multiprogramming — No.

d. Decrease the degree of multiprogramming — Yes.

e. Install more main memory — Likely to improve CPU utilization as more pages can remain resident and not require paging to or from the disks.

f. Install a faster hard disk, or multiple controllers with multiple hard disks — Also an improvement, as the disk bottleneck is removed by faster response and more throughput to the disks, the CPU will get more data more quickly.

g. Add prepaging to the page fetch algorithms — Again, the CPU will get more data faster, so it will be more in use. This is only the case if the paging action is amenable to prefetching (i.e., some of the access is sequential).

h. Increase the page size — Increasing the page size will result in fewer page faults if data is being accessed sequentially. If data access is more or less random, more paging action could ensue because fewer pages can be kept in memory and more data is transferred per page fault. So this change is as likely to decrease utilization as it is to increase it.

9.10 Consider the two-dimensional array *A*:

var *A*: **array** [1..100] **of array** [1..100] **of** *integer*;

where *A*[1][1] is at location 200, in a paged memory system with pages of size 200. A small process is in page 0 (locations 0 to 199) for manipulating the matrix; thus, every instruction fetch will be from page 0.

For three page frames, how many page faults are generated by the following array-initialization loops, using LRU replacement, and assuming page frame 1 has the process in it, and the other two are initially empty:

a.
```
for j := 1 to 100 do
    for i := 1 to 100 do
        A[i][j]:= 0;
```

b.
```
for i := 1 to 100 do
    for j := 1 to 100 do
        A[i][j]:= 0;
```

Answer: The array is stored row-major; that is, the first data page contains A[1,1], A[1,2]....A[2,100] and the second page contains A[3,1], A[3,2]....A[4,100] and so on.

a. The page reference string is

0, 1, 0, 2, 0, ..., 0, 49, 0, 1, 0, 2, 0, ..., 0, 49, ...

and thus there will be 5000 page faults.

b. The page reference string is

0, 1, 0, 2, 0, ..., 0, 49

and thus there will be 50 page faults.

9.11 Consider the following page reference string:

1, 2, 3, 4, 2, 1, 5, 6, 2, 1, 2, 3, 7, 6, 3, 2, 1, 2, 3, 6.

How many page faults would occur for the following replacement algorithms, assuming one, two, three, four, five, six, or seven frames? Remember all frames are initially empty, so your first unique pages will all cost one fault each.

- LRU replacement
- FIFO replacement
- Optimal replacement

Answer:

Number of frames	LRU	FIFO	Optimal
1	20	20	20
2	18	18	15
3	15	16	11
4	10	14	8
5	8	10	7
6	7	10	7
7	7	7	7

9.12 Suppose that we want to use a paging algorithm that requires a reference bit (such as second-chance replacement or working-set model), but the hardware does not provide one. Sketch how we could simulate a reference bit even if one were not provided by the hardware, or explain why it is not possible to do so. If it is possible, calculate what the cost would be.

Answer: We can use the valid / invalid bit supported in hardware to simulate the reference bit. Initially set the bit to invalid. On first reference a trap to the operating system is generated. The operating system will set a software bit to 1 and reset the valid / invalid bit to valid.

9.13 We have devised a new page-replacement algorithm that is complex, but we think that it may be optimal. In some contorted test cases, Belady's anomaly occurs. Is the new algorithm optimal? Explain your answer.

Answer: No.

9.14 Suppose your replacement policy (in a paged system) consists of regularly examining each page and discarding that page if it has not been used since the last examination. What would you gain and what would you lose by using this policy rather than LRU or second-chance replacement?

Answer: Both LRU and second chance (and most page-replacement algorithms) are invoked only when a new page is needed. By examining pages at regular intervals, a system would not keep in memory pages that are no longer being used, even if there were no other need for the frame as yet. Thus a pool of free frames would be available most of the time, and page replacement (in the traditional sense) would not be needed. Unless, of course, all pages were in active use, in which case more memory (additional frames) is probably needed anyway.

9.15 Segmentation is similar to paging, but uses variable-sized "pages." Define two segment-replacement algorithms based on FIFO and LRU page-replacement schemes. Remember that since segments are not the same size, the segment that is chosen to be replaced may not be big enough to leave enough consecutive locations for the needed segment. Consider strategies for systems where segments cannot be relocated, and those for systems where they can.

Answer:

- **FIFO**. Find the first segment large enough to accommodate the incoming segment. If relocation is not possible and no one segment is large enough, select a combination of segments whose memories are contiguous, which are "closest to the first of the list" and which can accommodate the new segment. If relocation is possible, rearrange the memory so that the first *N* segments large enough for the incoming segment are contiguous in memory. Add any leftover space to the free-space list in both cases.
- **LRU**. Select the segment that has not been used for the longest period of time and that is large enough, adding any leftover space to the free space list. If no one segment is large enough, select a combination of the "oldest" segments that are contiguous in memory (if relocation is not available) and that are large enough. If relocation is available, rearrange the oldest *N* segments to be contiguous in memory and replace those with the new segment.

9.16 A page-replacement algorithm should minimize the number of page faults. We can do this minimization by distributing heavily used pages evenly over all of memory, rather than having them compete for a small number of page frames. We can associate with each page frame a counter of the number of pages that are associated with that frame. Then, to replace a page, we search for the page frame with the smallest counter.

a. Define a page-replacement algorithm using this basic idea. Specifically address the problems of (1) what the initial value of the counters is, (2) when counters are increased, (3) when counters are decreased, and (4) how the page to be replaced is selected.

b. How many page faults occur for your algorithm for the following reference string, for four page frames?

1, 2, 3, 4, 5, 3, 4, 1, 6, 7, 8, 7, 8, 9, 7, 8, 9, 5, 4, 5, 4, 2.

c. What is the minimum number of page faults for an optimal page-replacement strategy for the reference string in part b with four page frames?

Answer:

a. Define a page-replacement algorithm addressing the problems of:
   i. Initial value of the counters — 0.
   ii. Counters are increased — whenever a new page is associated with that frame.
   iii. Counters are decreased — whenever one of the pages associated with that frame is no longer required.
   iv. How the page to be replaced is selected — find a frame with the smallest counter. Use FIFO for breaking ties.

b. 14 page faults

c. 11 page faults

9.17 Consider a demand-paging system with a paging disk that has an average access and transfer time of 20 milliseconds. Addresses are translated through a page table in main memory, with an access time of 1 microsecond per memory access. Thus, each memory reference through the page table takes two accesses. To improve this time, we have added an associative memory that reduces access time to one memory reference, if the page-table entry is in the associative memory.

Assume that 80 percent of the accesses are in the associative memory, and that, of the remaining, 10 percent (or 2 percent of the total) cause page faults. What is the effective memory access time?

Answer:

$$\begin{aligned}\text{effective access time} &= (0.8) \times (1\ \mu\text{sec}) \\ &\quad + (0.1) \times (2\ \mu\text{sec}) + (0.1) \times (5002\ \mu\text{sec}) \\ &= 501.2\ \mu\text{sec} \\ &= 0.5\ \text{millisec}\end{aligned}$$

9.18 Consider a demand-paged computer system where the degree of multiprogramming is currently fixed at four. The system was recently measured to determine utilization of CPU and the paging disk. The results are one of the following alternatives. For each case, what is happening? Can the degree of multiprogramming be increased to increase the CPU utilization? Is the paging helping?

a. CPU utilization 13 percent; disk utilization 97 percent

b. CPU utilization 87 percent; disk utilization 3 percent

c. CPU utilization 13 percent; disk utilization 3 percent

Answer:

a. Thrashing is occurring.

b. CPU utilization is sufficiently high to leave things alone. Can increase degree of multiprogramming.

c. Increase the degree of multiprogramming.

9.19 We have an operating system for a machine that uses base and limit registers, but we have modified the machine to provide a page table. Can the page tables be set up to simulate base and limit registers? How can they be, or why can they not be?

Answer: The page table can be set up to simulate base and limit registers provided that the memory is allocated in fixed size segments. In this way, the base of a segment can be entered into the page table and the valid/invalid bit used to indicate that portion of the segment as resident in the memory. There will be some problem with internal fragmentation.

9.20 What is the cause of thrashing? How does the system detect thrashing? Once it detects thrashing, what can the system do to eliminate this problem?

Answer: Thrashing is caused by underallocation of the minimum number of pages required by a process, forcing it to continuously page fault. The system can detect thrashing by evaluating the level of CPU utilization as compared to the level of multiprogramming. It can be eliminated by reducing the level of multiprogramming.

■ Review Questions

9.1 What is virtual memory?
Answer: A set of techniques and hardware allowing us to execute a program even when not entirely in memory.

9.2 List cases where entire program need not be in memory, traditionally.
Answer:

a. Certain options of a program that are rarely used.

b. Many error-handling sections.

c. Large arrays, lists, and tables, where only a small portion is used.

9.3 List benefits of having only part of a program in memory.
Answer:

a. Simplifies the programming task.

b. More user-programs can run concurrently in newly freed memory.

c. Less swapping of entire programs, thus less I/O.

9.4 What effect has virtual memory had on traditional program management?
Answer: Overlay methods have disappeared.

9.5 What is demand paging?
Answer: Design where a page is never swapped into memory unless needed.

9.6 List advantages of demand paging.
Answer: Decreases swap time and the amount of free physical memory, allows higher degree of multiprogramming.

9.7 Why is there a valid/invalid bit? Where is it kept?
Answer: To indicate whether an address is invalid, or a page is swapped out. It is kept in the page-frame table.

9.8 What is a page fault?
Answer: An interrupt caused by program needing a specific page not yet in memory.

9.9 List six steps to process a page fault.
Answer:

a. Check page-frame table in PCB. If address invalid, abort program.

b. If address valid, but its page not current, bring it in.

c. Find free frame.

d. Request I/O for the desired page.

e. Update the page-frame table in PCB.

f. Restart the instruction.

9.10 Indicate states of instruction execution when a page fault occurs.
Answer:

a. Page fault while fetching the instruction.

b. Page fault while fetching the operands.

c. Page fault while storing data to memory.

9.11 List two ways to resolve problem of instruction or data straddling two pages.
Answer:

a. Access both ends of both blocks involved to bring in all needed pages.

b. Save values needed for instructions and operands in temporary registers.

9.12 How do you compute the effective access time for a demand-page system?
Answer: Let p = probability of a page fault, t = memory access time, f = page-fault time. Then effective time = $(1 - p) \times t + p \times f$.

9.13 What factors determine f, the page-fault time?
Answer:

a. Time to service interrupt.

b. Time to swap page.

c. Time to restart process.

9.14 List ways of resolving problem of no free frames left.
Answer:

a. Aborting user program (poor solution).

b. Swap out an entire program, freeing its frames.

c. Replacing particular existing frames.

9.15 What is page replacement?
Answer: Selecting a frame (preferably not in use) as a victim; swap it out; swap in the desired page into this frame; restarting program.

9.16 How many swaps are needed for pure page replacement?
Answer: Two: first one out, second one in.

9.17 What does the modify (dirty) bit mean?
Answer: If set, the page has been modified, and must be written back to backing store before being used as a victim.

9.18 Ideally, what criteria should we use to replace pages?
Answer: Choose the victims to achieve the lowest page-fault rate.

9.19 We can judge page-replacement algorithms using what kind of data?
Answer: Reference strings: list of memory address references made by programs.

9.20 Describe FIFO as a page-replacement algorithm.
Answer: “First-in-First-out;” oldest page is chosen as victim, as determined by its position in a queue. Easy to understand; performance not always good.

9.21 What is Belady’s anomaly?
Answer: You’d expect that the page-fault rate would decrease as the number of frames increases; but Belady’s anomaly says this is not true in all algorithms.

9.22 What is the ideal page-replacement scheme?
Answer: OPTimal, or MINimum page-fault method. Replace the page that will not be used for the longest future time.

9.23 What are the uses and disadvantages of the OPT method?
Answer: It requires future knowledge of the reference string. It is used to compare with other methods.

9.24 What is the LRU algorithm?
Answer: Least recently used page is the victim of page replacement.

9.25 List ways to implement LRU, to determine which page is victim.
Answer:

a. Use hardware counter and / or clock. Page table contains time that is updated after each use. Page with oldest time is victim.

b. Use stack of page numbers. On each use, page number is moved to top of stack, and rest are shifted down. Bottom number is the victim.

c. Use a reference bit that is set after use, but cleared after time intervals. Victim is one with bit cleared.

d. Use a reference byte. After given time interval, the byte in each page is shifted right, but page in use has sign-bit set. Victim is page with lowest-valued byte.

9.26 Does LRU require extra hardware?
Answer: Yes. Otherwise, system would spend more time selecting victims than in running programs.

9.27 What is the second-chance replacement method?
Answer: Pages are arranged in FIFO order, but have a reference bit. Oldest page is selected; if bit is clear, it is the victim. If bit is set, we clear it and look at next page.

9.28 What is the LFU method?
Answer: It keeps the number of references made to each page, and shifts the count right after regular intervals. Page with lowest count is victim.

9.29 List two ways of distributing frames among processes.
Answer:

a. Each process uses same number, “equal allocation.”

b. Each process uses a number of frames proportional to the size of the process, “proportional allocation size.”

9.30 What problems occur with the above ways of distributing frames?
Answer:

a. You can’t allocate fractional parts of frames; each process uses the ceiling (number given).

b. Total number of frames can’t be more than exist.

c. May want to give some processes higher priority.

9.31 How do global and local allocation differ?
Answer:

- Local replacement: victim of replacement is in current process.
- Global replacement: victim of replacement selected from any process.

9.32 What is thrashing?
Answer: State where the system spends an excessive amount of time on paging, compared to the execution of processes.

9.33 Describe how CPU utilization varies with degree of multiprogramming.
Answer: At low degrees, usage is linear in degree; as degree rises, usage increases to a maximum, of order of $(1 - \exp(-\text{degree}))$. As degree increases further, thrashing occurs, and usage drops exponentially, $\exp(\text{thrashing} - \text{degree})$. See Figure 9.14.

9.34 What is meant by locality?
Answer: A set of pages which are actively used together.

9.35 What is a working set?
Answer: The set of pages referenced in the most recent time period delta, called the working set window.

9.36 What is the advantage of the working set model?
Answer: It allows you to determine a near optimum size for each process, and to allocate frames to prevent thrashing, yet with high degree of multiprogramming.

9.37 What is the page-fault frequency strategy?
Answer: Lower and upper levels of page-fault rates are specified. If a process faults more often than upper, it is given more frames; if it faults less than lower, frames are removed from it.

9.38 Why use prepaging?
Answer: Each process needs a minimum number of pages to run initially. Bring them in immediately to reduce paging later.

9.39 List factors determining the size of a page.
Answer:

a. A large page size will allow the page table size to be small.
b. To minimize internal fragmentation, the page size should be small.
c. To minimize I/O times, page size should be large.
d. The quantity of I/O is reduced for smaller pages, as locality is improved.
e. To minimize the number of page faults, need large pages.

9.40 Illustrate the statement: “system performance can be improved by an awareness of the underlying demand paging.”
Answer:

a. If a two-dimensional array is stored by rows, it should be accessed by rows, to avoid excess paging.
b. Stacks have good locality, hash tables produce poor locality.
c. Writing programs in reentrant fashion will prevent pages from becoming “dirty.”
d. Separating code and data allows each to be treated in a different locality and to be paged separately.

9.41 List two ways to treat memory swaps while waiting for I/O.
Answer:

a. Never execute I/O to user memory; thus allow the waiting process' pages to be swapped out.

b. Lock the pages waiting for I/O into memory using a lock bit.

9.42 Describe another use of the lock bit. What danger is there here?
Answer: To prevent a newly swapped-in page from being swapped out before it can be used. The danger is that the bit may never get turned off, and the frame could become unusable.

Chapter 10

FILE-SYSTEM INTERFACE

Files are the most obvious object that operating systems manipulate. Everything is typically stored in files: programs, data, output, etc. The student should learn what a file is to the operating system and what the problems are (providing naming conventions to allow files to be found by user programs, protection).

Two problems can crop up with this chapter. First, terminology may be different between your system and the book. This can be used to drive home the point that concepts are important and terms must be clearly defined when you get to a new system. Second, it may be difficult to motivate students to learn about directory structures that are not the ones on the system they are using. This can best be overcome if the students have two very different systems to consider, such as a single-user system for a microcomputer and a large, university time-shared system.

Projects might include a report about the details of the file system for the local system. It is also possible to write programs to implement a simple file system either in memory (allocate a large block of memory that is used to simulate a disk) or on top of an existing file system. In many cases, the design of a file system is an interesting project of its own.

■ Answers to Exercises

10.1 Consider a file system where a file can be deleted and its disk space reclaimed while links to that file still exist. What problems may occur if a new file is created in the same storage area or with the same absolute path name? How can these problems be avoided?

Answer: Let F1 be the old file and F2 be the new file. A user wishing to access F1 through an existing link will actually access F2. Note that the access protection for file F1 is used rather than the one associated with F2.

This problem can be avoided by insuring that all links to a deleted file are deleted also. This can be accomplished in several ways:

a. maintain a list of all links to a file, removing each of them when the file is deleted

b. retain the links, removing them when an attempt is made to access a deleted file

c. maintain a file reference list (or counter), deleting the file only after all links or references to that file have been deleted.

10.2 Some systems automatically delete all user files when a user logs off or a job terminates, unless the user explicitly requests that they be kept; other systems keep all files unless the user explicitly deletes them. Discuss the relative merits of each approach.

Answer: Deleting all files not specifically saved by the user has the advantage of minimizing the file space needed for each user by not saving unwanted or unnecessary files. Saving all files unless specifically deleted is more secure for the user in that it is not possible to inadvertently lose files by forgetting to save them.

10.3 Why do some systems keep track of the type of a file, while others leave it to the user or simply do not implement multiple file types? Which system is "better?"

Answer: Some systems allow different file operations based on the type of the file (for instance, an ascii file can be read as a stream while a database file can be read via an index to a block). Other systems leave such interpretation of a file's data to the process and provide no help in accessing the data. The method which is "better" depends on the needs of the processes on the system, and the demands the users place on the operating system. If a system runs mostly database applications, it may be more efficient for the operating system to implement a database-type file and provide operations, rather than making each program implement the same thing (possibly in different ways). For general purpose systems it may be better to only implement basic file types to keep the operating system size smaller and allow maximum freedom to the processes on the system.

10.4 Similarly, some systems support many types of structures for a file's data, while others simply support a stream of bytes. What are the advantages and disadvantages?

Answer: (See 10.3)

10.5 What are the advantages and disadvantages of recording the name of the creating program with the file's attributes (as is done in the Macintosh Operating System)?

Answer: By recording the name of the creating program, the operating system is able to implement features (such as automatic program invocation when the file is accessed) based on this information. It does add overhead in the operating system and require space in the file descriptor, however.

10.6 Could you simulate a multilevel directory structure with a single-level directory structure in which arbitrarily long names can be used? If your answer is yes, explain how you can do so, and contrast this scheme with the multilevel directory scheme. If your answer is no, explain what prevents your simulation's success. How would your answer change if file names were limited to seven characters?

Answer: If arbitrarily long names can be used then it is possible to simulate a multilevel directory structure. This can be done, for example, by using the character "." to indicate the end of a subdirectory. Thus, for example, the name *jim.pascal.F1* specifies that *F1* is a file in subdirectory *pascal* which in turn is in the root directory *jim*.

If file names were limited to seven characters, then the above scheme could not be utilized and thus, in general, the answer is *no*. The next best approach in this situation would be to use a specific file as a symbol table (directory) to map arbitrarily long names (such as *jim.pascal.F1*) into shorter arbitrary names (such as *XX00743*), which are then used for actual file access.

10.7 Explain the purpose of the **open** and **close** operations.

Answer:

- The *open* operation informs the system that the named file is about to become active.
- The *close* operation informs the system that the named file is no longer in active use by the user who issued the close operation.

10.8 Some systems automatically open a file when it is referenced for the first time, and close the file when the job terminates. Discuss the advantages and disadvantages of this scheme as compared to the more traditional one, where the user has to open and close the file explicitly.

Answer: Automatic opening and closing of files relieves the user from the invocation of these functions, and thus makes it more convenient to the user; however, it requires more overhead than the case where explicit opening and closing is required.

10.9 Give an example of an application in which data in a file should be accessed in the following order:

a. Sequentially

b. Randomly

Answer:

a. Print the content of the file.

b. Print the content of record *i*. This record can be found using hashing or index techniques.

10.10 Some systems provide file sharing by maintaining a single copy of a file; other systems maintain several copies, one for each of the users sharing the file. Discuss the relative merits of each approach.

Answer: With a single copy, several concurrent updates to a file may result in user obtaining incorrect information, and the file being left in an incorrect state. With multiple copies, there is storage waste and the various copies may not be consistent with respect to each other.

10.11 In some systems, a subdirectory can be read and written by an authorized user, just as ordinary files can be.

a. Describe the protection problems that could arise.

b. Suggest a scheme for dealing with each of the protection problems you named in part a.

Answer:

a. One piece of information kept in a directory entry is file location. If a user could modify this location, then he could access other files defeating the access-protection scheme.

b. Do not allow the user to directly write onto the subdirectory. Rather, provide system operations to do so.

10.12 Consider a system that supports 5000 users. Suppose that you want to allow 4990 of these users to be able to access one file.

a. How would you specify this protection scheme in UNIX?

b. Could you suggest another protection scheme that can be used more effectively for this purpose than the scheme provided by UNIX?

Answer:

a. There are two methods for achieving this:

i. Create an access control list with the names of all 4990 users.

ii. Put these 4990 users in one group and set the group access accordingly. This scheme cannot always be implemented since user groups are restricted by the system.

b. The universe access information applies to all users unless their name appears in the access-control list with different access permission. With this scheme you simply put the names of the remaining ten users in the access control list but with no access privileges allowed.

10.13 Researchers have suggested that, instead of having an access list associated with each file (specifying which users can access the file, and how), we should have a *user control list* associated with each user (specifying which files a user can access, and how). Discuss the relative merits of these two schemes.

Answer:

- *File control list*. Since the access control information is concentrated in one single place, it is easier to change access control information and this requires less space.
- *User control list*. This requires less overhead when opening a file.

■ Review Questions

10.1 What is a file?

Answer: A named collection of related data defined by the creator, recorded on secondary storage.

10.2 List sample file types, based on use, on the VAX under VMS.

Answer:

- source programs (.BAS, .FOR, .COB, .PLI, .PAS, .MAR)
- data files (.DAT)
- text files (.TXT)
- command procedures (.COM)
- mail files (.MAI)
- compiler-listing files (.LIS, .LST)
- object files (.OBJ)
- executable image files (.EXE)
- journal files (.JOU)

10.3 List some file types on the VAX under VMS.

Answer:

- source-language for programs (.BAS, .COB, .FOR, .MAR, .PAS, .PLI, ...)
- binary language (.OBJ, .EXE)
- ASCII code (.TXT)
- mail format (.MAI)

10.4 What does OPEN do?

Answer: Creates memory buffers, creates data control blocks, and creates other data structures needed for the I/O. If file is new, it also allocates space, and enters name in directory.

10.5 What does CLOSE do?

Answer: Outputs last buffer of information. Deletes buffers, data control blocks, and other data structures.

10.6 List advantages of operating system "knowing" and supporting many file types.

Answer: Can prevent user from making ridiculous mistakes. Can make system convenient to use by automatically doing various jobs after one command.

10.7 List the disadvantages of operating system "knowing" and supporting many file types.

Answer: Size of operating system becomes large. Every file type allowed must be defined, thus hinders in creating new file types.

10.8 What is a sequential file?

Answer: A file that is read one record or block or parameter at a time in order, based on a tape model of a file.

10.9 What is direct access?

Answer: A file in which any record or block can be read next. Usually the blocks are fixed length.

10.10 How does user specify block to be fetched in direct access?

Answer: By specifying the relative block number, relative to first block in file, which is block 0.

10.11 Can a direct access file be read sequentially? Explain.

Answer: Yes. Keep a counter, *cp*, initially set to 0. After reading record *cp*, increment *cp*.

10.12 How can an index file be used to speed up the access in direct-access files?

Answer: Have an index in memory; the index gives the key and the disk location of its corresponding record. Scan the index to find the record you want, and then access it directly.

10.13 Explain what ISAM is.

Answer: Indexed sequential access method. The file is stored in sorted order. ISAM has a master index file, indicating in what part of another index file the key you want is; the secondary index points to the file records. In both cases, a binary search is used to locate a record.

10.14 List two types of system directories

Answer:

a. Device directory, describing physical properties of files.

b. File directory, giving logical properties of the files.

10.15 List operations to be performed on directories.

Answer: Search for a file, create a file, delete a file, list a directory, rename a file, traverse the file system.

10.16 List disadvantages of using a single directory.

Answer: Users have no privacy. Users must be careful in choosing file names, to avoid names used by others. Users may destroy each others' work.

10.17 What is the MFD? UFD? How are they related?

Answer: MFD is master-file directory, which points to the UFDs. UFD is user-file directory, which points to each of user's files.

10.18 What advantages are there to this two-level directory?

Answer: Users are isolated from each other. Users have more freedom in choosing file names.

10.19 What disadvantages are there to this two-level directory?

Answer: Without other provisions, two users who want to cooperate with each other are hampered in reaching each other's files, and system files are inaccessible.

10.20 How do we overcome the disadvantages of the two-level directory?

Answer: Provide links from one user directory to another, creating path names; system files become available by letting the command interpreter search your directory first, and then the system directory if file needed is not in first directory.

10.21 What is a file path name?

Answer: A list of the directories, subdirectories, and files we must traverse to reach a file from the root directory.

10.22 If we use the two-level directory, how do we access common files and programs, like FORTRAN compiler? Show two or more ways.

Answer:

a. Keep copy of each common file in each user account.

b. Keep common files in a special account of system files, and translate the commands to path names to those files.

c. Permit path names from one directory to another.

10.23 Why would we want a subdirectory in our account?

Answer: To group files into collections of similar nature, and to protect certain groups of files from other users.

10.24 List steps you need to follow to delete a subdirectory in your account.

Answer: Delete all files in subdirectory. Change protection code to allow deletion, and then delete the subdirectory. This procedure must be followed, starting with the deepest subdirectory.

10.25 What is an acyclic graph?

Answer: A tree that has been corrupted by links to other branches, but does not have any cyclic paths in it.

10.26 List ways to share files between directories in operating systems.

Answer:

a. Copy file from one account into another.

b. Link directory entry of “copied” file to directory entry of original file.

c. Copy directory entry of file into account file is “copied” into.

10.27 What problems might arise on deletion if a file is shared?

Answer: Copier of file might delete the original shared file, depriving rest of users. They have a pointer to a deleted directory entry pointing to the original file or one overwritten by other users of the system, or a new entry pointing to a new file created by the original user.

10.28 How can we solve this problem?

Answer: Keep a count of the number of links to a file in original directory. As each person deletes a file, the count decreases by 1.

10.29 What is a general graph?

Answer: A tree structure where links can go from one branch to a node earlier in the same branch or other branch, allowing cycles.

10.30 What problems arise if the directory structure is a general graph?

Answer: Searching for a particular file may result in searching the same directory many times. Deletion of the file may result in the reference count to be nonzero even when no directories point to that file.

10.31 What is garbage collection?

Answer: Determining what file space is available, and making it available for users. (Note: garbage collection is also done in BASIC, to reclaim space used by deleted strings.)

10.32 How can we protect files on a single-user system?

Answer:

a. Hide the disks.

b. Use file names that can't be read.

c. Backup disks.

d. On floppies, place a write-disable-tab on.

10.33 What might damage files?

Answer: Hardware errors, power surges, power failures, disk-head crashes (read / write head scraping magnetic material off disk), dirt, temperature, humidity, software bugs, fingerprints on magnetic material, bent disk or cover, vandalism by other users, storing diskettes near strong magnets which are found in CRTs, radio speakers, and so on.

10.34 List kinds of access we might want to limit on a multiuser system.

Answer: Reading files in given account; creating, writing, or modifying files in given account; executing files in given account; deleting files in given account.

10.35 List four ways systems might provide for users to protect their files against other users.

Answer:

a. Allowing user to use unprintable characters in naming files so other users can't determine the complete name.

b. Assigning password(s) to each file that must be given before access is allowed.

c. Assigning an access list, listing everyone who is allowed to use each file.

d. Assigning protection codes to each file, classifying users as system, owner, group, and world (everyone else).

Chapter 11

FILE-SYSTEM IMPLEMENTATION

In this chapter we discuss various methods for storing information on secondary storage. The basic issues are device directory, free space management, and space allocation on a disk.

Answers to Exercises

11.1 Consider a file currently consisting of 100 blocks. Assume that the file control block (and the index block, in the case of indexed allocation) is already in memory. Calculate how many disk I/O operations are required for contiguous, linked, and indexed (single-level) allocation strategies, if, for one block, the following conditions hold. In the contiguous-allocation case, assume that there is no room to grow in the beginning, but there is room to grow in the end. Assume that the block information to be added is stored in memory.

a. The block is added at the beginning.

b. The block is added in the middle.

c. The block is added at the end.

d. The block is removed from the beginning.

e. The block is removed from the middle.

f. The block is removed from the end.

Answer:

	Contiguous	Linked	Indexed
a.	201	1	1
b.	101	52	1
c.	1	3	1
d.	198	1	0
e.	98	52	0
f.	0	100	0

11.2 Consider a system where free space is kept in a free-space list.

a. Suppose that the pointer to the free-space list is lost. Can the system reconstruct the free-space list? Explain your answer.

b. Suggest a scheme to ensure that the pointer is never lost as a result of memory failure.

Answer:

a. In order to reconstruct the free list, it would be necessary to perform "garbage collection." This would entail searching the entire directory structure to determine which pages are already allocated to jobs. Those remaining unallocated pages could be relinked as the free-space list.

b. The free-space list pointer could be stored on the disk, perhaps in several places.

11.3 What problems could occur if a system allowed a file system to be mounted simultaneously at more than one location?
Answer: There would be multiple paths to the same file, which could confuse users or encourage mistakes (deleting a file with one path deletes the file in all the other paths).

11.4 Why must the bit map for file allocation be kept on mass storage, rather than in main memory?
Answer: In case of system crash (memory failure) the free-space list would not be lost as it would be if the bit map had been stored in main memory.

11.5 Consider a system that supports the strategies of contiguous, linked, and indexed allocation. What criteria should be used in deciding which strategy is best utilized for a particular file?
Answer:

- **Contiguous** – if file is usually accessed sequentially, if file is relatively small.
- **Linked** – if file is large and usually accessed sequentially.
- **Indexed** – if file is large and usually accessed randomly.

11.6 Consider a file system on a disk that has both logical and physical block sizes of 512 bytes. Assume that the information about each file is already in memory. For each of the three allocation strategies (contiguous, linked, and indexed), answer these questions:

a. How is the logical-to-physical address mapping accomplished in this system? (For the indexed allocation, assume that a file is always less than 512 blocks long.)

b. If we are currently at logical block 10 (the last block accessed was block 10) and want to access logical block 4, how many physical blocks must be read from the disk?

Answer: Let Z be the starting file address (block number).

a. Contiguous. Divide the logical address by 512 with X and Y the resulting quotient and remainder respectively.

   i. Add X to Z to obtain the physical block number. Y is the displacement into that block.

   ii. 1

b. Linked. Divide the logical physical address by 511 with X and Y the resulting quotient and remainder respectively.

   i. Chase down the linked list (getting $X + 1$ blocks). $Y + 1$ is the displacement into the last physical block.

   ii. 4

c. Indexed. Divide the logical address by 512 with X and Y the resulting quotient and remainder respectively.

   i. Get the index block into memory. Physical block address is contained in the index block at location X. Y is the displacement into the desired physical block.

   ii. 2

11.7 One problem with contiguous allocation is that the user must preallocate enough space for each file. If the file grows to be larger than the space allocated for it, special actions must be taken. One solution to this problem is to define a file structure consisting of an initial contiguous area (of a specified size). If this area is filled, the operating system automatically defines an overflow area that is linked to the initial contiguous area. If the overflow area is filled, another overflow area is allocated. Compare this implementation of a file with the standard contiguous and linked implementations.

Answer: This method requires more overhead then the standard contiguous allocation. It requires less overhead than the standard linked allocation.

11.8 Fragmentation on a storage device could be eliminated by recompaction of the information. Typical disk devices do not have relocation or base registers (such as are used when memory is to be compacted), so how can we relocate files? Give three reasons why recompacting and relocation of files often are avoided.

Answer: Relocation of files on secondary storage involves considerable overhead — data blocks would have to be read into main memory and written back out to their new locations. Furthermore, relocation registers apply only to *sequential* files, and many disk files are not sequential. For this same reason, many new files will not require contiguous disk space; even sequential files can be allocated noncontiguous blocks if links between logically sequential blocks are maintained by the disk system.

11.9 How do caches help improve performance? Why do systems not use more or larger caches if they are so useful?

Answer: Caches allow components of differing speeds to communicate more efficiently by storing data from the slower device, temporarily, in a faster device (the cache). Caches are, almost by definition, more expensive than the device they are caching for, so increasing the number or size of caches would increase system cost.

11.10 In what situations would using memory as a RAM disk be more useful than using it as a disk cache?

Answer: In cases where the user (or system) knows exactly what data is going to be needed. Caches are algorithm-based, while a RAM disk is user-directed.

11.11 Why is it advantageous for the user for an operating system to dynamically allocate its internal tables? What are the penalties to the operating system for doing so?

Answer: Dynamic tables allow more flexibility in system use growth — tables are never exceeded, avoiding artificial use limits. Unfortunately, kernel structures and code are more complicated, so there is more potential for bugs. The use of one resource can take away more system resources (by growing to accommodate the requests) than with static tables.

11.12 Consider the following backup scheme:

- **Day 1**. Copy to a backup medium all files from the disk.
- **Day 2**. Copy to another medium all files changed since day 1.
- **Day 3**. Copy to another medium all files changed since day 1.

This contrasts to the schedule given in Section 11.6.2 by having all subsequent backups copy all files modified since the first full backup. What are the benefits of this system over the one in Section 11.6.2? What are the drawbacks? Are restore operations made easier or more difficult? Explain your answer.
Answer: Restores are easier because you can go to the last backup tape, rather than the full tape. No intermediate tapes need be read. More tape is used as more files change.

■ Review Questions

11.1 List three ways of allocating storage, and give advantages of each.
Answer:

a. Contiguous allocation. Fastest, if no changes are to be made. Also easiest for random-access files.

b. Linked allocation. No external fragmentation. File can grow without complications.

c. Indexed allocation. Supports direct access without external fragmentation.

11.2 What is contiguous allocation?
Answer: Allocation of a group of consecutive sectors for a single file.

11.3 What main difficulty occurs with contiguous allocation?
Answer: Finding space for a new file.

11.4 What is a "hole" in contiguous allocation method?
Answer: An unallocated segment of blocks.

11.5 Explain first-fit, best-fit, and worst-fit methods of allocating space for contiguous files.
Answer:

- First-fit: Scan available blocks of disk for successive free sectors; use the first area found that has sufficient space; do not scan beyond that point.
- Best-fit: Search for smallest area large enough to place the file.
- Worst-fit: Search for largest area in which to place the file.

11.6 What is external fragmentation in a system with contiguous files?
Answer: The disk has files scattered all over; fragmentation occurs when there is enough empty space collectively for the next file, but there is no single gap large enough for the entire file to fit in.

11.7 How can we overcome fragmentation?
Answer: We can use an allocation technique that does not result in fragmentation; or we can move the files around on disk, putting them closer together, to leave us larger blocks of available sectors.

11.8 What is preallocation? Why do it?
Answer: Allocating space for a file before creating the file to allow for expansion. This reserves space for a particular file so that other files can't grab it. The new file may initially use only a small portion of this space.

11.9 What is linked allocation, as detailed in text?
Answer: Directory contains pointers to first and last blocks of file. Each block of file (except last) has pointer to the next block.

11.10 Can linked allocation have external fragmentation? Internal fragmentation?
Answer: External — no. Internal — Yes.

11.11 Can linked allocation be used for direct-access files?
Answer: Not in the form suggested in the book. RSTS on the PDP-11 stores the sector numbers in the directory, with each group of seven addresses linked to the next group of seven. Direct access using this modified linked allocation is possible. (This approach is really a hybrid of linked and indexed allocations.)

11.12 What is indexed allocation?
Answer: Each file has its own block of pointers to the sectors of the file.

11.13 Rank the allocation methods on speed.
Answer: Contiguous is fastest. Linked is slower, because the disk head may have to move between accesses of file. Indexed is slowest, unless the entire index can be kept in memory at all times. If not, then extra time must be used to access next block of file indexes.

11.14 List four ways a system could use to determine which sectors are free. Give advantages of each way.
Answer:

a. Free-space list. Each section indicates a sector that is available. Not encumbered by a used-sector list.

b. Bit vector is a compact version. Has no links that can be broken.

c. Link all free sectors together in an available list. Takes no usable space. But links could break.

d. List giving start of each block of free sectors, and a count of number of sectors in this block. This is fast for use in contiguous storage search.

11.15 List kinds of information we'd likely want to keep in a directory, and estimate number of bytes needed to store each compactly.
Answer: File name (5 - 15), file type (3), location (4), size (2), protection (2), usage count (2), time (2), date (2), process ID (3), time-date-process ID for creation, last modification, last use (3-4 bytes for each time / date), owner (2).

11.16 What data structures can be used for directory information?
Answer:

a. Linear list

b. Linked list

c. Sorted list

d. Linked binary tree

e. Hash table

11.17 What problems might arise with above data structures?
Answer:

a. Linear list is slow to access particular file. Also must decide how to take care of deletions (mark, copy last entry to it, ...).

b. Linked list requires storage overhead for pointers; also, if link goes bad, rest of files are lost.

c. Sorted list requires list always to be sorted, which means extra work on creating and deleting files.

d. Binary tree suffers like linked list.

e. Hash tables are set up for a maximum number of files; also there is a problem with collisions.

11.18 Give advantages of each directory structure above.
Answer:

Linear list	Simple to program search.
Linked list	Easier to process deletes.
Sorted list	Fast access.
Linked binary tree	Faster access.
Hash table	Fastest access.

Chapter 12

I/O SYSTEMS

The role of the operating system in computer I/O is to manage and control I/O operations and I/O devices. Although related topics appear in other chapters, here we bring together the pieces to paint a complete picture. In this chapter we describe I/O Structure, Devices, Device Drivers, Caching, and Terminal I/O.

■ Answers to Exercises

12.1 State three advantages of placing functionality in a device controller, rather than in the kernel. State three disadvantages.

Answer: Three advantages: Bugs are less likely to cause an operating system crash

Performance can be improved by utilizing dedicated hardware and hard-coded algorithms

The kernel is simplified by moving algorithms out of it

Three disadvantages: Bugs are harder to fix - a new firmware version or new hardware is needed

Improving algorithms likewise require a hardware update rather than just kernel or device driver update

Embedded algorithms could conflict with application's use of the device, causing decreased performance.

12.2 Consider the following I/O scenarios on a single-user PC.

a. A mouse used with a graphical user interface

b. A tape drive on a multitasking operating system (assume no device preallocation is available)

c. A disk drive containing user files

d. A graphics card with direct bus connection, accessible through memory-mapped I/O

For each of these I/O scenarios, would you design the operating system to use buffering, spooling, caching, or a combination? Would you use polled I/O, or interrupt-driven I/O? Give reasons for your choices.

Answer:

a. A mouse used with a graphical user interface
Buffering may be needed to record mouse movement during times when higher-priority operations are taking place. Spooling and caching are inappropriate. Interrupt driven I/O is most appropriate.

b. A tape drive on a multitasking operating system (assume no device preallocation is available)
Buffering may be needed to manage throughput difference between the tape drive and the source or destination of the I/O, Caching can be used to hold copies of data that resides on the tape, for faster access. Spooling could be used to stage data to the device when multiple users desire to read from or write to it. Interrupt driven I/O is likely to allow the best performance.

c. A disk drive containing user files
Buffering can be used to hold data while in transit from user space to the disk, and visa versa. Caching can be used to hold disk-resident data for improved performance. Spooling is not necessary because disks are shared-access devices. Interrupt-driven I/O is best for devices such as disks that transfer data at slow rates.

d. A graphics card with direct bus connection, accessible through memory-mapped I/O
Buffering may be needed to control multiple access and for performance (double-buffering can be used to hold the next screen image while displaying the current one). Caching and spooling are not necessary due to the fast and shared-access natures of the device. Polling and interrupts are only useful for input and for I/O completion detection, neither of which is needed for a memory-mapped device.

12.3 The example of handshaking in Section 12.1 used 2 bits: a **busy** bit and a **command-ready** bit. Is it possible to implement this handshaking with only 1 bit? If it is, describe the protocol. If it is not, explain why 1 bit is insufficient.

Answer: No answer.

12.4 Describe three circumstances under which blocking I/O should be used. Describe three circumstances under which nonblocking I/O should be used. Why not just implement nonblocking I/O and have processes busy-wait until their device is ready?

Answer:

Generally, blocking I/O is appropriate when the process will only be waiting for one specific event. Examples include a disk, tape, or keyboard read by an application program. Non-blocking I/O is useful when I/O may come from more than one source and the order of the I/O arrival is not predetermined. Examples include network daemons listening to more than one network socket, window managers that accept mouse movement as well as keyboard input, and I/O-management programs, such as a copy command that copies data between I/O devices. In the last case, the program could optimize its performance by buffering the input and output and using non-blocking I/O to keep both devices fully occupied.

Non-blocking I/O is more complicated for programmers, because of the asynchonous rendezvous that is needed when an I/O occurs. Also, busy waiting is less efficient than interrupt-driven I/O so the overall system performance would decrease.

12.5 Why might a system use interrupt-driven I/O to manage a single serial port, but polling I/O to manage a front-end processor, such as a terminal concentrator?

Answer: Polling can be more efficient than interrupt-driven I/O. This is the case when the I/O is frequent and of short duration. Even though a single serial port will perform I/O relatively infrequently and should thus use interrupts, a collection of serial ports such as those in a terminal concentrator can produce a lot of short I/O operations, and interrupting for each one could create a heavy load on the system. A well-timed polling loop could alleviate that load without wasting many resources through looping with no I/O needed.

12.6 Polling for an I/O completion can waste a large number of CPU cycles if the processor iterates a busy-waiting loop many times before the I/O completes. But if the I/O device is ready for service, polling can be much more efficient than is catching and dispatching an interrupt. Describe a hybrid strategy that combines polling, sleeping, and interrupts for I/O device service. For each of these three strategies (pure polling, pure interrupts, hybrid), describe a computing environment in which that strategy is more efficient than is either of the others.

Answer: No answer.

12.7 UNIX coordinates the activities of the kernel I/O components by manipulating shared in-kernel data structures, whereas Windows NT uses object-oriented message passing between kernel I/O components. Discuss three pros and three cons of each approach.

Answer:

Three pros of the UNIX method: Very efficient, low overhead and low amount of data movement

Fast implementation — no coordination needed with other kernel components

Simple, so less chance of data loss

Three cons: No data protection, and more possible side-effects from changes so more difficult to debug

Difficult to implement new I/O methods: new data structures needed rather than just new objects

Complicated kernel I/O subsystem, full of data structures, access routines, and locking mechanisms

12.8 How does DMA increase system concurrency? How does it complicate hardware design?

Answer:

DMA increases system concurrency by allowing the CPU to perform tasks while the DMA system transfers data via the system and memory busses. Hardware design is complicated because the DMA controller must be integrated into the system, and the system must allow the DMA controller to be a bus master. Cycle stealing may also be necessary to allow the CPU and DMA controller to share use of the memory bus.

12.9 Write (in pseudocode) an implementation of virtual clocks, including the queuing and management of timer requests for the kernel and applications. Assume that the hardware provides three timer channels.

Answer: No answer.

12.10 Why is it important to scale up system bus and device speeds as the CPU speed increases?

Answer:

Consider a system which performs 50% I/O and 50% computes. Doubling the CPU performance on this system would increase total system performance by only 50%. Doubling both system aspects would increase performance by 100%. Generally, it is important to remove the current system bottleneck, and to increase overall system performance, rather than blindly increasing the performance of individual system components.

Chapter 13

SECONDARY-STORAGE STRUCTURE

In this chapter we describe the internal data structures and algorithms used by the operating system to implement this interface. We also discuss the lowest level of the file system — the secondary storage structure. We first describe disk-head-scheduling algorithms. Next we discuss disk formatting and management of boot blocks, damaged blocks, and swap space. We end with coverage of disk reliability and stable-storage.

The basic implementation of disk scheduling should be fairly clear: requests, queues, servicing, so the main new consideration is the actual algorithms: FCFS, SSTF, SCAN, C-SCAN, LOOK, C-LOOK, and sector queueing. Simulation may be the best way to involve the student with the algorithms.

The paper by Teory and Pinkerton [1972] seems to be the best presentation of the disk-scheduling algorithms and their evaluation. The paper by Lynch [1972b] is also important since it shows the importance of keeping the overall system context in mind when choosing scheduling algorithms. Unfortunately, it is fairly difficult to find.

■ Answers to Exercises

13.1 None of the disk-scheduling disciplines, except FCFS, are truly fair (starvation may occur).

a. Explain why this assertion is true.

b. Describe a way to modify algorithms such as SCAN to ensure fairness.

c. Explain why fairness is an important goal in a time-sharing system.

d. Give three or more examples of circumstances in which it is important that the operating system be *un*fair in serving I/O requests.

Answer:

a. New requests for the track over which the head currently resides can theoretically arrive as quickly as these requests are being serviced.

b. All requests older than some predetermined age could be “forced” to the top of the queue and an associated bit for each could be set to indicate that no new request could be moved ahead of these requests. For SSTF, the rest of the queue would have to be reorganized with respect to the last of these “old” requests.

c. To prevent unusually long response times.

d. No answer.

13.2 Suppose that a disk drive has 5000 cylinders, numbered 0 to 4999. The drive is currently serving a request at cylinder 143, and the previous request was at cylinder 125. The queue of pending requests, in FIFO order, is

86, 1470, 913, 1774, 948, 1509, 1022, 1750, 130.

Starting from the current head position, what is the total distance (in cylinders) that the disk arm moves to satisfy all the pending requests, for each of the following disk-scheduling algorithms?

a. FCFS

b. SSTF

c. SCAN

d. LOOK

e. C-SCAN

Answer: No answer.

13.3 From elementary physics, we know that, when an object is subjected to a constant acceleration a, the relationship between distance d and time t is given by $d = \frac{1}{2}at^2$. Suppose that, during a seek, the disk in Exercise 13.2 accelerates the disk arm at a constant rate for the first half of the seek, then decelerates the disk arm at the same rate for the second half of the seek. Assume that the disk can perform a seek to an adjacent cylinder in 1 millisecond, and a full-stroke seek over all 5000 cylinders in 18 milliseconds.

a. The distance of a seek is the number of cylinders that the head moves. Explain why the seek time is proportional to the square root of the seek distance.

b. Write an equation for the seek time as a function of the seek distance. This equation should be of the form $t = x + y\sqrt{L}$, where t is the time in milliseconds, and L is the seek distance in cylinders.

c. Calculate the total seek time for each of the schedules in Exercise 13.2. Determine which schedule is the fastest (has the smallest total seek time).

d. The *percentage speedup* is the time saved divided by the original time. What is the percentage speedup of the fastest schedule over FCFS?

Answer: No answer.

13.4 Suppose that the disk in Exercise 13.3 rotates at 7200 RPM.

a. What is the average rotational latency of this disk drive?

b. What seek distance can be covered in the time that you found for part a?

Answer: No answer.

13.5 The accelerating seek described in Exercise 13.3 is typical of hard-disk drives. By contrast, floppy disks (and many hard disks manufactured before the mid-1980s) typically seek at a fixed rate. Suppose that the disk in Exercise 13.3 has a constant-rate seek, rather than a constant-acceleration seek, so the seek time is of the form $t = x + yL$, where t is the time in milliseconds, and L is the seek distance. Suppose that the time to seek to an adjacent cylinder is 1 millisecond, as before, and is 0.5 milliseconds for each additional cylinder.

a. Write an equation for this seek time as a function of the seek distance.

b. Using the seek-time function from part a, calculate the total seek time for each of the schedules in Exercise 13.2. Is your answer the same as it was for Exercise 13.3(c)?

c. What is the percentage speedup of the fastest schedule over FCFS in this case?

Answer: No answer.

13.6 Write a monitor-type program (see Chapter 6) for disk scheduling using the SCAN and C-SCAN disk-scheduling algorithms.
Answer: We provide only the solution for C-SCAN.

```
type diskhead = monitor
var  busy: boolean;
     up: condition;
     headpos, count: integer;

procedure entry acquire (dest: integer);
     begin
          if busy
             then if headpos ≤ dest
                      then up.wait(dest + count)
                      else up.wait(dest + count+n);
          busy := true;
          if dest < headpos
             then count := count + n;
          headpos := dest;
     end;

procedure entry release;
     begin
          busy := false;
          up.signal;
     end;

begin
     headpos := 0;
     count := 0;
end.
```

13.7 Compare the performance of C-SCAN and SCAN scheduling, assuming a uniform distribution of requests. Consider the average response time (the time between the arrival of a request and the completion of that request's service), the variation in response time, and the effective bandwidth. How does performance depend on the relative sizes of seek time and rotational latency?

Answer: The main difference would be that C-SCAN loses time traveling from the inside edge to the outside edge of the disk. Other, quite minor differences in throughput could come from the fact that SCAN examines the edge tracks once for two examinations of the inside tracks and the time intervals between successive visits of a given track tend to have a greater variance for SCAN than for C-SCAN.

13.8 Is disk scheduling, other than FCFS scheduling, useful in a single-user environment? Explain your answer.

Answer: In a single-user environment, the I/O queue is usually of length 1. Therefore FCFS would be the most economical method for disk scheduling.

13.9 Explain why SSTF scheduling tends to favor middle cylinders over the innermost and outermost cylinders.

Answer: The center of the disk is the location having the smallest average distance to all other tracks. Thus after servicing the first request, the algorithm would be more likely to be closer to the center track than to any other particular track, and hence would more often go there first.

Once at a particular track, SSTF tends to keep the head near this track; thus, this scheduling strategy would compound the initial tendency to go to the center.

13.10 Requests are not usually uniformly distributed. For example, a cylinder containing the file system FAT or inodes can be expected to be accessed more frequently than a cylinder that only contains files. Suppose that you know that 50 percent of the requests are for a small, fixed number of cylinders.

a. Would any of the scheduling algorithms discussed in this chapter be particularly good for this case? Explain your answer.

b. Propose a disk-scheduling algorithm that gives even better performance by taking advantage of this “hot spot” on the disk.

c. File systems typically find data blocks via an indirection table, such as a FAT in DOS or inodes in UNIX. Describe one or more ways to take advantage of this indirection to improve the disk performance.

Answer:

a. SSTF would take greatest advantage of the situation. FCFS could cause unnecessary head movement if references to the “high-demand” cylinders were interspersed with references to cylinders far away.

b. One suggestion: SSTF with some modification to prevent starvation.
Second suggestion: (A variation of SCAN) The head is allowed to make one “zigzag” over the high-volume tracks. An upper limit on the number of consecutive requests (on the same track) that can be serviced before moving on would prevent starvation.

c. No answer.

13.11 Why is rotational latency usually not considered in disk scheduling? How would you modify SSTF, SCAN, and C-SCAN to include latency optimization?

Answer: A timing problem arises: the program that would do the latency-time ordering needs to know the number of the sector that would be underneath the head at the time of I/O service. This information would have to come immediately before servicing the I/O request in order to be accurate. This would require extra communication with the peripheral which would take time, canceling some of the benefit.

13.12 How would the use of a RAM disk affect your selection of a disk-scheduling algorithm? What factors would you need to consider? Do the same considerations apply to hard-disk scheduling, given that the file system stores recently used blocks in a buffer cache in main memory?

Answer: There is no seek time nor latency on a RAM disk, so those factors can be ignored. In fact, there is no need to schedule RAM disk accesses because they all occur at the same speed, no matter what has happened previously.

13.13 Why is it important to balance file system I/O among the disks and controllers on a system in a multitasking environment?

Answer: A system can only perform at the speed of its slowest bottleneck. Disks or disk controllers are frequently the bottleneck in modern systems as their individual performance cannot keep up with that of the CPU and system bus. By balancing I/O among disks and controllers, neither an individual disk nor a controller is overwhelmed, so that bottleneck is avoided.

13.14 What are the tradeoffs involved in rereading code pages from the file system, versus using swap space to store them?

Answer: If code pages are stored in swap space, they can be transferred more quickly to main memory (because swap space allocation is tuned for faster performance than general file system allocation). Using swap space can require startup time if the pages are copied there at process invocation, rather than just being paged out to swap space on demand. Also, more swap space must be allocated if it is used for both code and data pages.

13.15 Is there any way to implement truly stable storage? Explain your answer.

Answer: Truly stable storage would require that data never be lost. “Never” is a big word. Global cataclysmic disaster, for instance, would wipe out storage of data no matter how many copies of it exist on which media. If data is shot into space for secure keeping, then there is always the possibility of the universe collapsing...

13.16 The reliability of a hard-disk drive is typically described in terms of a quantity called *mean time between failures* (*MTBF*). Although this quantity is called a “time,” the MTBF actually is measured in drive-hours per failure.

a. If a disk farm contains 1000 drives, each of which has a 750,000 hour MTBF, which of the following best describes how often a drive failure will occur in that disk farm: once per thousand years, once per century, once per decade, once per year, once per month, once per week, once per day, once per hour, once per minute, or once per second?

b. Mortality statistics indicate that, on the average, a U.S. resident has about 1 chance in 1000 of dying between ages 20 and 21 years. Deduce the MTBF hours for 20 year olds. Convert this figure from hours to years. What does this MTBF tell you about the expected lifetime of a 20 year old?

c. The manufacturer claims a 1-million hour MTBF for a certain model of disk drive. What can you say about the number of years that one of those drives can be expected to last?

Answer: No answer.

13.17 The term “fast wide SCSI-II” denotes a SCSI bus that operates at a data rate of 20 megabytes per second when it moves a packet of bytes between the host and a device. Suppose that a fast wide SCSI-II disk drive spins at 7200 RPM, has a sector size of 512 bytes, and holds 160 sectors per track.

a. Estimate the sustained transfer rate of this drive in megabytes per second.

b. Suppose that the drive has 7000 cylinders, 20 tracks per cylinder, a head switch time (from one platter to another) of 0.5 milliseconds, and an adjacent cylinder seek time of 2 milliseconds. Use this additional information to give an accurate estimate of the sustained transfer rate for a huge transfer.

c. Suppose that the average seek time for the drive is 8 milliseconds. Estimate the I/Os per second and the effective transfer rate for a random-access workload that reads individual sectors that are scattered across the disk.

d. Calculate the random-access I/Os per second and transfer rate for I/O sizes of 4 kilobytes, 8 kilobytes, and 64 kilobytes.

e. If multiple requests are in the queue, a scheduling algorithm such as SCAN should be able to reduce the average seek distance. Suppose that a random-access workload is reading 8-kilobyte pages, the average queue length is 10, and the scheduling algorithm reduces the average seek time to 3 milliseconds. Now calculate the I/Os per second and the effective transfer rate of the drive.

Answer: No answer.

13.18 More than one disk drive can be attached to a SCSI bus. In particular, a fast wide SCSI-II bus (see Exercise 13.17) can be connected to at most 15 disk drives. Recall that this bus has a bandwidth of 20 megabytes per second. At any time, only one packet can be transferred on the bus between some disk's internal cache and the host. However, a disk can be moving its disk arm while some other disk is transferring a packet on the bus. Also, a disk can be transferring data between its magnetic platters and its internal cache while some other disk is transferring a packet on the bus. Considering the transfer rates that you calculated for the various workloads in Exercise 13.17, discuss how many disks can be used effectively by one fast wide SCSI-II bus.

Answer: No answer.

13.19 The fact that bad blocks are remapped by sector sparing or sector slipping could have a performance impact. Suppose that the drive in Exercise 13.17 has a total of 100 bad sectors at random locations, and that each bad sector is mapped to a spare that is located on a different track, but within the same cylinder. Estimate the I/Os per second and the effective transfer rate for a random-access workload consisting of 8-kilobyte reads, with a queue length of 1 (so the choice of scheduling algorithm is not a factor). What is the performance impact of the bad sectors?

Answer: No answer.

13.20 Discuss the relative merits of sector sparing and sector slipping.

■ Review Questions

13.1 What is a sector? track? cylinder?
Answer:

- Sector — smallest block that can be read or written on a disk.
- Track — collection of sectors all on same circumference on a single surface.
- Cylinder — collection of all tracks of same radius on a multiplatter disk.

13.2 How is information on the disk referenced?
Answer: By the drive number, surface, track, and sector.

13.3 Describe how multiplatter disks are organized into tracks and sectors.
Answer: The disks have from three to twenty platters rotating concentrically together. Each platter has two surfaces (except outer platters sometimes do not have outer surfaces), giving us N surfaces. These platters are divided up into C concentric cylinders, all rotating together around the same axis. The intersection of a cylinder with a surface is called a track, a circle on a single surface. Each track is divided up into K circular segments called sectors. So, the number of sectors on a disk = $N \times C \times K$.

13.4 What is seek time?
Answer: Time for the read / write head to find the desired cylinder.

13.5 What is latency time?
Answer: Time for the disk to rotate to the start of the desired sector.

13.6 What characteristics determine the disk access speed?
Answer:

a. Seek time: time for head to reach specified track.
b. Latency time: determined by rate of rotation.
c. Transfer time: determined by rate of rotation, amount of data to be transferred, and the density of the data on the disk.

13.7 What information is needed for disk I/O?
Answer:

a. Whether input or output.
b. Disk address.
c. Memory address.
d. Amount of data to be moved.

13.8 What is the problem with FCFS scheduling with disks?
Answer: Head may swing wildly from track to track, temporarily skipping some tracks that need to be used. Very inefficient.

13.9 What is SSTF scheduling with disks?
Answer: Shortest-Seek-Time-First: processes I/O in tracks closest to the current position of the head.

13.10 What disadvantage does SSTF have?
Answer: May result in starvation of some requests, if most requests are clustered together within a few tracks, but the others are far away.

13.11 Describe the SCAN algorithm.
Answer: Start with lowest track with an I/O request, and process requests in track order, until highest is found; then proceed in reverse order.

13.12 How does the C-SCAN method vary from the SCAN method?
Answer: After reaching highest track number request, it returns to the lowest track number request, without processing any en route.

13.13 Where should the disk directories be placed?
Answer: Near the middle tracks.

Chapter 14

TERTIARY-STORAGE STRUCTURE

Chapter 2 introduced the concept of primary, secondary, and tertiary storage. In this chapter, we discuss tertiary storage in more detail. First we describe the types of storage devices used for tertiary storage. Next, we discuss the issues that arise when an operating system uses tertiary storage. Finally, we consider some performance aspects of tertiary storage systems.

■ Answers to Exercises

14.1 The operating system generally treats removable disks as shared file systems, but assigns a tape drive to only one application at a time. Give three reasons that could explain this difference in treatment of disks and tapes. Describe additional features that would be required of the operating system to support shared file-system access to a tape jukebox. Would the applications sharing the tape jukebox need any special properties, or could they use the files as though the files were disk-resident? Explain your answer.
Answer:

a. Disks have fast random-access times, so they give good performance for interleaved access streams. By contrast, tapes have high positioning times. Consequently, if two users attempt to share a tape drive for reading, the drive will spend most of its time switching tapes and positioning to the desired data, and relatively little time performing data transfers. This performance problem is similar to the thrashing of a virtual memory system that has insufficient physical memory.

b. Tape cartridges are removable. The owner of the data may wish to store the cartridge off-site (far away from the computer) to keep a copy of the data safe from a fire at the location of the computer.

c. Tape cartridges are often used to send large volumes of data from a producer of data to the consumer. Such a tape cartridge is reserved for that particular data transfer, and cannot be used for general-purpose shared storage space.

To support shared file-system access to a tape jukebox, the operating system would need to perform the usual file system duties, including

- Manage a file-system name space over the collection of tapes
- Perform space allocation
- Schedule the I/O operations

The applications that access a tape-resident file system would need to be tolerant of lengthy delays. For improved performance, it would be desirable for the applications to be able to disclose a large number of I/O operations so that the tape scheduling algorithms could generate efficient schedules.

14.2 In a disk jukebox, what would be the effect of having more open files than the number of drives in the jukebox?

Answer: Two bad outcomes could result. One possibility is starvation of the applications that issue blocking I/Os to tapes that are not mounted in drives. Another possibility is thrashing, as the jukebox is commanded to switch tapes after every I/O operation.

14.3 Consider hierarchical storage management, data archiving, and backups. Discuss which uses of tertiary storage would best be implemented as operating-system functions, and which are just useful applications.

Answer: No Answer

14.4 What would be the effect on cost and performance if tape storage were to achieve the same areal density as disk storage?

Answer: To achieve the same areal density as a magnetic disk, the areal density of a tape would need to improve by 2 orders of magnitude. This would cause tape storage to be much cheaper than disk storage. The storage capacity of a tape would increase to more than 1 terabyte, which could enable a single tape to replace a jukebox of tapes in today's technology, further reducing the cost. The areal density has no direct bearing on the data transfer rate, but the higher capacity per tape might reduce the overhead of tape switching.

14.5 If magnetic hard disks had the same cost per gigabyte as do tapes, would tapes become obsolete, or would they still be needed? Discuss your answer.

Answer: Tapes are easily removable, so they are useful for off-site backups and for bulk transfer of data (by sending cartridges). As a rule, a magnetic hard disk is not a removable medium.

14.6 Let us use some simple estimates to compare the cost and performance of a terabyte storage system made entirely from disks with one that incorporates tertiary storage. Suppose that magnetic disks each hold 10 gigabytes, cost $1000, transfer 5 megabytes per second, and have an average access latency of 15 milliseconds. Suppose that a tape library costs $10 per gigabyte, transfers 10 megabytes per second, and has an average access latency of 20 seconds. Compute the total cost, the maximum total data rate, and the average waiting time for a pure disk system. (Do you need to make any assumptions about the workload? If you do, what are they?) Now, suppose that 5 percent of the data are frequently used, so they must reside on disk, but the other 95 percent are archived in the tape library. And suppose that 95 percent of the requests are handled by the disk system, and the other 5 percent are handled by the library. What are the total cost, the maximum total data rate, and the average waiting time for this hierarchical storage system?

Answer: First let's consider the pure disk system. One terabyte is 1024 GB. To be correct, we need 103 disks at 10 GB each. But since this question is about approximations, we will simplify the arithmetic by rounding off the numbers. The pure disk system will have 100 drives. The cost of the disk drives would be $100,000, plus about 20% for cables, power supplies, and enclosures, i.e., around \$120,000. The aggregate data rate would be 100×5 MB/s, or 500 MB/s. The average waiting time depends on the workload. Suppose that the requests are for transfers of size 8 KB, and suppose that the requests are randomly distributed over the disk drives. If the system is lightly loaded, a typical request will arrives at an idle disk, so the response time will be 15 ms access time plus about 2 ms transfer time. If the system is heavily loaded, the delay will increase, roughly in proportion to the queue length.

Now let's consider the hierarchical storage system. The total disk space required is 5% of 1 TB, which is 50 GB. Consequently, we need 5 disks, so the cost of the disk storage is \$5,000 (plus 20%, i.e., \$6,000). The cost of the 950 GB tape library is \$9500. Thus the total storage cost is \$15,500. The maximum total data rate depends on the number of drives in the tape library. We suppose there is only 1 drive. Then the aggregate data rate is 6×10 MB/s, i.e., 60 MB/s. For a lightly-loaded system, 95% of the requests will be satisfied by the disks with a delay of about 17 ms. The other 5% of the requests will be satisfied by the tape library, with a delay of slightly more than 20 seconds. Thus the average delay will be $(95 \times 0.017 + 5 \times 20)/100$, or about 1 second. Even with an empty request queue at the tape library, the latency of the tape drive is responsible for almost all of the system's response latency, because $1/20^{th}$ of the workload is sent to a device that has a 20 second latency. If the system is more heavily loaded, the average delay will increase in proportion to the length of the queue of requests waiting for service from the tape drive.

The hierarchical system is much cheaper. For the 95% of the requests that are served by the disks, the performance is as good as a pure-disk system. But the maximum data rate of the hierarchical system is much worse than for the pure-disk system, as is the average response time.

14.7 It is sometimes said that tape is a sequential-access medium, whereas magnetic disk is a random-access medium. In fact, the suitability of a storage device for random access depends on the transfer size. The term *streaming transfer rate* denotes the data rate for a transfer that is underway, excluding the effect of access latency. By contrast, the *effective transfer rate* is the ratio of total bytes per total seconds, including overhead time such as the access latency.

Suppose that, in a computer, the level 2 cache has an access latency of 8 nanoseconds and a streaming transfer rate of 800 megabytes per second, the main memory has an access latency of 60 nanoseconds and a streaming transfer rate of 80 megabytes per second, the magnetic disk has an access latency of 15 millisecond and a streaming transfer rate of 5 megabytes per second, and a tape drive has an access latency of 60 seconds and a streaming transfer rate of 2 megabytes per seconds.

a. Random access causes the effective transfer rate of a device to decrease, because no data are transferred during the access time. For the disk described, what is the effective transfer rate if an average access is followed by a streaming transfer of 512 bytes, 8 kilobytes, 1 megabyte, and 16 megabytes?

b. The utilization of a device is the the ratio of effective transfer rate to streaming transfer rate. Calculate the utilization of the disk drive for random access that performs transfers in each of the four sizes given in part a.

c. Suppose that a utilization of 25% (or higher) is considered acceptable. Using the performance figures given, compute the smallest transfer size for disk that gives acceptable utilization.

d. Complete the following sentence: A disk is a random-access device for transfers larger than ______ bytes, and is a sequential-access device for smaller transfers.

e. Compute the minimum transfer sizes that give acceptable utilization for cache, memory, and tape.

f. When is a tape a random-access device, and when is it a sequential-access device?

Answer:

a. For the disk, the transfer time (excluding access time) is calculated as $\frac{bytes}{bytespersecond}$. The effective transfer rate is the number of bytes divided by the number of seconds. For 512 bytes, the transfer time is about 0.1 millisecond, so the total time is about 15.1 milliseconds, and the effective transfer rate is about 34,000 bytes per second. Similarly, for 8 kilobytes, the transfer time is about 1.6 ms, so the effective transfer rate is about 490,000 bytes per second. For 1 MB, the effective transfer rate is about 4,900,000 bytes per second, and for 16 MB, the effective transfer rate is 5,218,419 bytes per second.

b. At 512 bytes, the utilization is about 34,000 / 5,242,880, i.e., about 0.65%. At 8 KB, the utilization is about 9.3%, at 1 MB the utilization is about 93.5

c. A 25% utilization means that 1 / 4 of the time is spent transferring data, and 3 / 4 of the time is spent on access overhead—1 unit of transfer for 3 units of overhead. Since the access overhead is 15 milliseconds, the corresponding transfer time is 5 ms. The streaming rate is 5 MB / s, i.e., 5242.88 bytes per ms. Thus the amount of data transferred in 5 ms is 26,214 bytes: this is the transfer size that gives 25% utilization.

d. We say that a device is a random-access device if we can do data transfers from randomly-chosen locations and still get an acceptable effective transfer rate. Under the assumptions of the problem, a disk is a random-access device for transfers larger than 26,214 bytes, and a sequential-access device for smaller transfers. As an aside, we note that the Solaris file system attempts to allocate space for large files in units of 56 KB, to achieve an acceptable effective transfer rate for the file system.

e. For cache, the access overhead is 8 ns. For 25% utilization, each data transfer takes 8 / 3 ns, and thus the transfer size that achieves 25% utilization is 2.2 bytes. For memory, the transfer time for 25% utilization is 20 ns, and the amount of data transferred in this amount of time is 16.8 bytes. For tape, the transfer time for 25% utilization is 20 seconds, so the corresponding transfer size is 40 megabytes.

f. Tape is a random-access device for sufficiently large transfers (e.g., 40 megabytes or larger). For smaller transfers, it is necessary to use the tape drive as a sequential-access device to obtain an acceptable device utilization.

14.8 What if a holographic storage drive were invented? Suppose that a holographic drive costs $10,000 and has an average access time of 40 milliseconds. Suppose that it uses a $100 cartridge the size of a CD. This cartridge holds 40,000 images, and each image is a square black-and-white picture with resolution 6000×6000 pixels (each pixel stores 1 bit). Suppose that the drive can read or write 1 picture in 1 millisecond. Discuss the following questions.

a. What would be some good uses for this device?

b. How would this device affect the I / O performance of a computing system?

c. Which other kinds of storage devices, if any, would become obsolete as a result of this device being invented?

Answer:

a. This device holds about 4.5 MB per image, the streaming transfer rate is about 4.5 GB/s, and the total capacity per cartridge is about 180 GB. Using the techniques of question 14.7, the transfer size needed for 25% utilization is 60 MB. A drive with a single cartridge has a cost per gigabyte of about \$56. By comparison with magnetic hard disk, the streaming transfer rate is nearly 1000 times higher, the cost is about the same, but the practical transfer size is very large. So this technology will not replace magnetic disks, but could work well as the tertiary-storage component of a hierarchical storage system. It would also be suitable for high-speed data storage, such as for satellite telemetry data. The cost of storage for a cartridge "on the shelf" (i.e., not in the drive) is about \$0.56, making this technology suitable as an inexpensive, high-performance storage medium for backups in large systems.

b. The transfer rate of this device is higher than the memory bandwidth of many computer systems, so it would tend to saturate a small computing system.

c. The storage cost and performance characteristics of this storage device would cause the obsolescence of high-end tape systems.

14.9 Suppose that a one-sided 5.25 inch optical-disk cartridge has an areal density of 1 gigabit per square inch. Suppose that a magnetic tape has an areal density of 20 megabits per square inch, and is 1/2 inch wide and 1800 feet long. Calculate an estimate of the storage capacities of these two kinds of storage cartridges. Suppose that an optical tape existed that had the same physical size as the tape, but the same storage density as the optical disk. What volume of data could it hold? What would be a fair price for the optical tape if the magnetic tape cost \$25?

Answer: The area of a 5.25 inch disk is about 19.625 square inches. If we suppose that the diameter of the spindle hub is 1.5 inches, the hub occupies an area of about 1.77 square inches, leaving 17.86 square inches for data storage. Therefore, we estimate the storage capacity of the optical disk to be 2.2 gigabytes.

The surface area of the tape is 10,800 square inches, so its storage capacity is about 26 gigabytes.

If the 10,800 square inches of tape had a storage density of 1 gigabit per square inch, the capacity of the tape would be about 1,350 gigabytes, or 1.3 terabytes. If we charge the same price per gigabyte for the optical tape as for magnetic tape, the optical tape cartridge would cost about 50 times more than the magnetic tape, i.e., \$1,250.

14.10 Suppose that we agree that 1 kilobyte is 1024 bytes, 1 megabyte is 1024^2 bytes, and 1 gigabyte is 1024^3 bytes. This progression continues through terabytes, petabytes, and exabytes (1024^6). Scientists estimate that a few enormous geological and astronomical research projects plan to record and store a few exabytes of data during the next decade. To answer the following questions, you will need to make a few reasonable assumptions; state the assumptions that you make.

a. How many disk drives would be required to hold 4 exabytes of data?

b. How many magnetic tapes would be required to hold 4 exabytes of data?

c. How many optical tapes would be required to hold 4 exabytes of data (see Exercise 14.9)?

d. How many holographic storage cartridges would be required to hold 4 exabytes of data (see Exercise 14.8)?

e. How many cubic feet of storage space would each option require?

Answer:

a. Assume that a disk drive holds 10 GB. Then 100 disks hold 1 TB, 100,000 disks hold 1 PB, and 100,000,000 disks hold 1 EB. To store 4 EB would require about 400 million disks. If a magnetic tape holds 40 GB, only 100 million tapes would be required. If an optical tape holds 50 times more data than a magnetic tape, 2 million optical tapes would suffice. If a holographic cartridge can store 180 GB, about 22.2 million cartridges would be required.

b. A 3.5” disk drive is about 1” high, 4” wide, and 6” deep. In feet, this is 1/12 by 1/3 by 1/2, or 1/72 cubic feet. Packed densely, the 400 million disks would occupy 5.6 million cubic feet. If we allow a factor of 2 for air space and space for power supplies, the required capacity is about 11 million cubic feet.

c. A 1/2” tape cartridge is about 1” high, and 4.5” square. The volume is about 1/85 cubic feet. For 100 million magnetic tapes packed densely, the volume is about 1.2 million cubic feet. For 2 million optical tapes, the volume is 23,400 cubic feet.

d. A CD-ROM is 4.75” in diameter and about 1/16” thick. If we assume that a holostore disk is stored in a library slot that is 5” square and 1/8” wide, we calculate the volume of 22.2 million disks to be about 40,000 cubic feet.

14.11 Discuss how an operating system could maintain a free-space list for a tape-resident file system. Assume that the tape technology is append-only, and that it uses the EOT mark and **locate**, **space**, and **read position** commands as described in Section 14.2.1.

Answer: Since this tape technology is append-only, all the free space is at the end of the tape. The location of this free space does not need to be stored at all, because the **space** command can be used to position to the EOT mark. The amount of available free space after the EOT mark can be represented by a single number. It may be desirable to maintain a second number to represent the amount of space occupied by files that have been logically deleted (but their space has not been reclaimed since the tape is append-only), so that we can decide when it would pay to copy the nondeleted files to a new tape in order to reclaim the old tape for reuse. We can store the free and deleted space numbers on disk for easy access. Another copy of these numbers can be stored at the end of the tape as the last data block. We can overwrite this last data block when we allocate new storage on the tape.

Chapter 15

NETWORK STRUCTURES

There are basically two schemes for building distributed systems. In a *multiprocessor* (tightly coupled) system, the processors share memory and a clock, and communication usually takes place through the shared memory. In a *distributed* (loosely coupled) system, the processors do not share memory or a clock. Instead, each processor has its own local memory. The processors communicate with one another through various communication networks, such as high-speed buses or telephone lines. In this chapter, we discuss the general structure of distributed systems and the networks that interconnect them. Detailed discussions are given in Chapters 16 to 18.

■ Answers to Exercises

15.1 Contrast the various network topologies in terms of reliability.

Answer:

- Fully connected — very reliable since all the links must fail to partition the system.
- Partially connected — not as reliable as a fully connected system because the failure of relatively few links (possibly 1) can partition the system.
- Hierarchy — the failure of any node (except a leaf) will partition the system into several disjoint subtrees.
- Star — if the central site fails, the entire network is partitioned.
- Ring — in a bidirectional ring, two links, and in a unidirectional, one link must fail to partition the system.
- Multi-Access Bus — The failure of one site does not affect the communications between the rest of the sites; however if the link fails, the network is completely partitioned.

15.2 Why do most WANs employ only a partially connected topology?

Answer: Fully connected topologies require by definition a connection from each node to every other node. Such connections are expensive, especially when there are lots of nodes and they are far apart.

15.3 What are the main differences between a WAN and a LAN?

Answer: The main difference is the way in which they are geographically distributed. Computer networks are composed of a number of autonomous processors that are distributed over a large geographical area (like the U.S.). Local-area networks are composed of processors that are distributed over small geographical areas (like a single building).

15.4 What network configuration would best suit the following environments?

a. A dormitory floor

b. A university campus

c. A state

d. A nation

Answer:

a. Multiaccess bus.

b. Ring structure.

c. Partially connected network.

d. Partially connected network.

15.5 Even though the ISO model of networking specifies seven layers of functionality, most computer systems use fewer layers to implement a network. Why do they use fewer layers? What problems could the use of fewer layers cause?

Answer: No Answer

15.6 Explain why a doubling of the speed of the systems on an Ethernet segment may result in decreased network performance. What changes could be made to ameliorate the problem?

Answer: Faster systems may be able to send more packets in a shorter amount of time. The network would then have more packets traveling on it, resulting in more collisions, and therefore less throughput relative to the number of packets being sent. More networks can be used, with fewer systems per network, to reduce the number of collisions.

15.7 Under what circumstances is a token-ring network more effective than an Ethernet network?

Answer: A token ring is very effective under high sustained load, as no collisions can occur and each slot may be used to carry a message, providing high throughput. A token ring is less effective when the load is light (token processing takes longer than bus access, so any one packet can take longer to reach its destination), or sporadic.

15.8 Why would it be a bad idea for gateways to pass broadcast packets between networks? What would be the advantages of doing so?

Answer: All broadcasts would be propagated to all networks, causing a *lot* of network traffic. If broadcast traffic were limited to important data (and very little of it), then broadcast propagation would save gateways from having to run special software to watch for this data (such as network routing information) and rebroadcast it.

15.9 In what ways is using a name server better than using static host tables? What are the problems and complications associated with name servers? What methods could be used to decrease the amount of traffic name servers generate to satisfy translation requests?

Answer: Name servers require their own protocol, so they add complication to the system. Also, if a name server is down, host information may become unavailable. Backup name servers are required to avoid this problem. Caches can be used to store frequently-requested host information to cut down on network traffic.

15.10 The original *HTTP* protocol used TCP/IP as the underlying network protocol. For each page, graphic, or applet, a separate TCP session was contructed, used, and torn down. Because of the overhead of building and destroying TCP/IP connections, there were performance problems with this implementation method. Would using UDP rather than TCP have been a good alternative? What other changes could be made to improve HTTP performance?

Answer: No answer.

15.11 Of what use is an address resolution protocol? Why is the use of such a protocol better than making each host read each packet to determine to whom it is destined? Does a token-ring network need such a protocol?

Answer: An ARP translates general-purpose addresses into hardware interface numbers so the interface can know which packets are for it. Software need not get involved. It is more efficient than passing each packet to the higher layers. Yes, for the same reason.

Chapter 16

DISTRIBUTED-SYSTEM STRUCTURES

Chapter 16 examines distributed-system structures, including coverage of remote services, thread-management, and the Open Software Foundation's Distributed Computing Environment (DCE) thread package.

■ Answers to Exercises

16.1 What are the advantages and disadvantages of making the computer network transparent to the user?

Answer: The advantage is that all files are accessed in the same manner. The disadvantage is that the operating system becomes more complex.

16.2 What are the formidable problems that designers must solve to implement a network transparent system?

Answer: No Answer

16.3 Process migration within a heterogeneous network is usually impossible, given the differences in architectures and operating systems. Describe a method for process migration across different architectures running:

a. The same operating system

b. Different operating systems

Answer: No Answer

16.4 To build a robust distributed system, you must know what kinds of failures can occur.

a. List possible types of failure in a distributed system.

b. Specify which items in your list also are applicable to a centralized system.

Answer: No Answer

16.5 Is it always crucial to know that the message you have sent has arrived at its destination safely? If your answer is "yes," explain why. If your answer is "no," give appropriate examples.

Answer: No. Many status-gathering programs work from the assumption that packets may not be received by the destination system. These programs generally *broadcast* a packet and assume that at least some other systems on their network will receive the information. For instance a daemon on each system might broadcast the systems load average and number of users. This information might be used for process migration target selection. Another example is a program that determines if a remote site is both running and accessible over the network. If it sends a query and gets no reply it knows the system cannot currently be reached.

16.6 Present an algorithm for reconstructing a logical ring after a process in the ring fails.

Answer: A scheme similar to one of the election algorithms to be discussed in Section 18.6 can be used.

16.7 Consider a distributed system with two sites, A and B. Consider whether site A can distinguish among the following:

a. B goes down.

b. The link between A and B goes down.

c. B is extremely overloaded and response time is 100 times longer than normal.

What implications does your answer have for recovery in distributed systems?

Answer: No Answer

Chapter 17

DISTRIBUTED-FILE SYSTEMS

Chapter 17 looks at the current major research and development in distributed-file systems (DFS). The purpose of a DFS is to support the same kind of sharing when the files are physically dispersed among the various sites of a distributed system.

We discuss the various ways a distributed file system can be designed and implemented. First, we discuss common concepts on which distributed file systems are based. Then, we illustrate our concepts by examining the UNIX United, NFS, Andrew, Sprite, and Locus distributed file systems. By exploring these example systems, we hope to provide a sense of the considerations involved in designing an operating system, and also to indicate current areas of operating-system research: network and distributed operating systems.

■ Answers to Exercises

17.1 What are the benefits of a DFS when compared to a file system in a centralized system?
Answer: A DFS allows the same type of sharing available on a centralized system, but the sharing may occur on physically and logically separate systems. Users across the world are able to share data as if they were in the same building, allowing a much more flexible computing environment than would otherwise be available.

17.2 Which of the example DFSs would handle a large, multiclient database application most efficiently? Explain your answer.
Answer: No Answer

17.3 Under which circumstances would a client prefer a location-transparent DFS? Under which would she prefer a location-independent DFS? Discuss the reasons for these preferences.
Answer: Location-transparent DFS is good enough in systems in which files are not replicated. Location-independent DFS is necessary when any replication is done.

17.4 What aspects of a distributed system would you select for a system running on a totally reliable network?
Answer: Since the system is totally reliable, a stateful approach would make the most sense. Error recovery would seldom be needed, allowing the features of a stateful system

to be used. If the network is very fast as well as reliable, caching can be done on the server side. On a slower network caching on both server and client will speed performance, as would file location-independence and migration. Additionally, RPC-based service is not needed in the absence of failures, since a key part of its design is recovery during networking errors. Virtual-circuit systems are simpler and more appropriate for systems with no communications failures.

17.5 Compare and contrast the techniques of caching disk blocks locally, on a client system, and remotely, on a server.

Answer: No Answer

17.6 What are the benefits of mapping objects into virtual memory, as Apollo Domain does? What are the detriments?

Answer: Mapping objects into virtual memory greatly eases the sharing of data between processes. Rather than opening a file, locking access to it, and reading and writing sections via the I/O system calls, memory-mapped objects are accessible as "normal" memory, with reads and writes to locations independent of disk pointers. Locking is much easier also, since one shared memory location can be used as a locking variable for semaphore access. Unfortunately, memory mapping adds complexity to the operating system, especially in a distributed system.

Chapter 18

DISTRIBUTED COORDINATION

Chapter 18 examines various mechanisms for process synchronization and communication, as well as methods for dealing with the deadlock problem, in a distributed environment. In addition, since a distributed system may suffer from a variety of failures that are not encountered in a centralized system, we also discuss here the issue of failure in a distributed system.

■ Answers to Exercises

18.1 Discuss the advantages and disadvantages of the two methods we presented for generating globally unique timestamps.

Answer: No Answer.

18.2 Your company is building a computer network, and you are asked to write an algorithm for achieving distributed mutual exclusion. Which scheme will you use? Explain your choice.

Answer: The token passing algorithm of Section 18.2.3 avoids the problems of the fully distributed approach of Section 18.2.2 without suffering from the limitations of Section 18.2.2.

18.3 Why is deadlock detection much more expensive in a distributed environment than it is in a centralized environment?

Answer: Deadlock detection is a very high communications-overhead problem. In a distributed environment, communications is more expensive than on central systems. Therefore, the cost of deadlock detection goes up when done on distributed systems.

18.4 Your company is building a computer network, and you are asked to develop a scheme for dealing with the deadlock problem.

a. Would you use a deadlock-detection scheme, or a deadlock-prevention scheme?

b. If you were to use a deadlock-prevention scheme, which one would you use? Explain your choice.

c. If you were to use a deadlock-detection scheme, which one would you use? Explain your choice.

Answer:

a. Deadlock detection, to prevent unnecessary rollbacks.

b. The wound-wait scheme is the better general purpose solution because older processes are given higher priority and allowed to complete execution.

c. The fully distributed approach of Section 13.4.3 solves the problem most completely, but is complicated to implement and requires high overhead.

18.5 Consider the following *hierarchical* deadlock-detection algorithm, in which the global wait-for graph is distributed over a number of different *controllers,* which are organized in a tree. Each nonleaf controller maintains a wait-for graph that contains relevant information from the graphs of the controllers in the subtree below it. In particular, let S_A, S_B, and S_C be controllers such that S_C is the lowest common ancestor of S_A and S_B (S_C must be unique, since we are dealing with a tree). Suppose that node T_i appears in the local wait-for graph of controllers S_A and S_B. Then, T_i must also appear in the local wait-for graph of

- Controller S_C
- Every controller in the path from S_C to S_A
- Every controller in the path from S_C to S_B

In addition, if T_i and T_j appear in the wait-for graph of controller S_D and there exists a path from T_i to T_j in the wait-for graph of one of the children of D, then an edge $T_i \rightarrow T_j$ must be in the wait-for graph of S_D.
Show that, if a cycle exists in any of the wait-for graphs, then the system is deadlocked.
Answer: No Answer

18.6 Derive an election algorithm for bidirectional rings that is more efficient than the one presented in this chapter. How many messages are needed for n processes?
Answer: No Answer

18.7 Consider a failure that occurs during two-phase commit for a transaction. For each possible failure, explain how two-phase commit ensures transaction atomicity despite the failure.
Answer: No Answer

Chapter 19

PROTECTION

The various processes in an operating system must be protected from one another's activities. For that purpose, various 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.

In this chapter, we examine the problem of protection in great detail and develop a unifying model for implementing protection.

It is important that the student learn the concepts of the access matrix, access lists, and capabilities. Capabilities have been used in several modern systems and can be tied in with abstract data types. The paper by Lampson [1971] is the classic reference on protection.

■ Answers to Exercises

19.1 What are the main differences between capability lists and access lists?

Answer: An access list is a list for each object consisting of the domains with a nonempty set of access rights for that object. A capability list is a list of objects and the operations allowed on those objects for each domain.

19.2 A Burroughs B7000/B6000 MCP file can be tagged as sensitive data. When such a file is deleted, its storage area is overwritten by some random bits. For what purpose would such a scheme be useful?

Answer: This would be useful as an extra security measure so that the old content of memory cannot be accessed, either intentionally or by accident, by another program. This is especially useful for any highly classified information.

19.3 In a ring-protection system, level 0 has the greatest access to objects and level n (greater than zero) has fewer access rights. The access rights of a program at a particular level in the ring structure are considered as a set of capabilities. What is the relationship between the capabilities of a domain at level j and a domain at level i to an object (for $j > i$)?

Answer: D_j is a subset of D_i.

19.4 Consider a system in which “computer games” can be played by students only between 10 P.M. and 6 A.M., by faculty members between 5 P.M. and 8 A.M., and by the computer center staff at all times. Suggest a scheme for implementing this policy efficiently.

Answer: Set up a dynamic protection structure that changes the set of resources available with respect to the time allotted to the three categories of users. As time changes, so does the domain of users eligible to play the computer games. When the time comes that a user's eligibility is over, a revocation process must occur. Revocation could be immediate, selective (since the computer staff may access it at any hour), total, and temporary (since rights to access will be given back later in the day).

19.5 The RC 4000 system (and other systems) have defined a tree of processes (called a process tree) such that all the descendants of a process are given resources (objects) and access rights by their ancestors only. Thus, a descendant can never have the ability to do anything that its ancestors cannot do. The root of the tree is the operating system, which has the ability to do anything. Assume the set of access rights was represented by an access matrix, A. $A(x,y)$ defines the access rights of process x to object y. If x is a descendant of z, what is the relationship between $A(x,y)$ and $A(z,y)$ for an arbitrary object y?

Answer: $A(x,y)$ is a subset of $A(z,y)$.

19.6 What hardware features are needed for efficient capability manipulation? Can these be used for memory protection?

Answer: No Answer

19.7 Consider a computing environment where a unique number is associated with each process and each object in the system. Suppose that we allow a process with number n to access an object with number m only if $n > m$. What type of protection structure do we have?

Answer: Hierarchical structure.

19.8 What protection problems may arise if a shared stack is used for parameter passing?

Answer: No Answer

19.9 Consider a computing environment where a process is given the privilege of accessing an object only n times. Suggest a scheme for implementing this policy.

Answer: Add an integer counter with the capability.

19.10 If all the access rights to an object are deleted, the object can no longer be accessed. At this point, the object should also be deleted, and the space it occupies should be returned to the system. Suggest an efficient implementation of this scheme.

Answer: Reference counts.

19.11 What is the need-to-know principle? Why is it important for a protection system to adhere to this principle?

Answer: A process may access at any time those resources that it has been authorized to access *and* are required currently to complete its task. It is important in that it limits the amount of damage a faulty process can cause in a system.

19.12 Why is it difficult to protect a system in which users are allowed to do their own I/O?

Answer: No Answer

19.13 Capability lists are usually kept within the address space of the user. How does the system ensure that the user cannot modify the contents of the list?

Answer: No Answer

Chapter 20

SECURITY

The information stored in the system (both data and code), as well as the physical resources of the computer system, need to be protected from unauthorized access, malicious destruction or alteration, and accidental introduction of inconsistency. In this chapter, we examine the ways in which information may be misused or intentionally made inconsistent. We then present mechanisms to guard against this occurrence.

■ Answers to Exercises

20.1 A password may become known to other users in a variety of ways. Is there a simple method for detecting that such an event has occurred? Explain your answer.

Answer: Whenever a user logs in, the system prints the last time that user was logged on the system.

20.2 The list of all passwords is kept within the operating system. Thus, if a user manages to read this list, password protection is no longer provided. Suggest a scheme that will avoid this problem. (Hint: Use different internal and external representations.)

Answer: Encrypt the passwords internally so that they can only be accessed in coded form. The only person with access or knowledge of decoding should be the system operator.

20.3 An experimental addition to UNIX allows a user to connect a *watchdog* program to a file, such that the watchdog is invoked whenever a program requests access to the file. The watchdog then either grants or denies access to the file. Discuss the pros and cons of using watchdogs for security.

Answer: No Answer

20.4 The UNIX program, COPS, scans a given system for possible security holes and alerts the user to possible problems. What are the potential hazards of using such a system for security? How can these problems be limited or eliminated?

Answer: The COPS program itself could be modified by an intruder to disable some of its features, or even to take advantage of its features to create new security flaws. Even if COPS is not cracked, it is possible for an intruder to gain a copy of COPS, study it, and locate security breaches which COPS does not detect. Then that intruder could prey on systems in which the management depends on COPS for security (thinking it is providing security), when all COPS is providing is management complacency. COPS could be stored on a read only media or file system to avoid its modification. It could only be provided to bona fide systems managers to avoid it falling into the wrong hands. Neither of these is a foolproof solution however.

20.5 Discuss ways by which managers of systems connected to the Internet could have limited or eliminated the damage done by the worm. What are the drawbacks of making such changes to the way in which the system operates?

Answer: "Firewalls" can be erected between systems and the Internet. These systems filter the packets moving from one side of them to the other, assuring that only valid packets owned by authorized users are allowed to access the protect systems. Such firewalls usually make the use of the systems less convenient (and network connections less efficient).

20.6 Argue for or against the sentence handed down against Robert Morris, Jr., for his creation and execution of the Internet worm.

Answer: No answer

20.7 Make a list of security concerns for a computer system for a bank. For each item on your list, state whether this concern relates to physical security, human security, or operating system security.

Answer: In a protected location, well guarded: physical, human.
Network tamperproof: physical, human, operating system.
Modem access eliminated or limited: physical, human.
Unauthorized data transfers prevented or logged: human, operating system.
Backup media protected and guarded: physical, human.
Programmers, data entry personnel, trustworthy: human.

20.8 What are the advantages of encrypting data stored in the computer system?

Answer: Encrypted data are guarded by the operating system's protection facilities, as well as a password which is needed to decrypt them. Two keys are better than one when it comes to security.

Chapter 21

THE UNIX SYSTEM

Although operating system concepts can be considered in purely theoretical terms, it is often useful to see how they are implemented in practice. This chapter presents an in-depth examination of the 4.3BSD operating system, a version of UNIX, as an example of the various concepts presented in this book. By examining a complete, real system, we can see how the various concepts discussed in this book relate both to one another and to practice.

This UNIX operating system was chosen in part because at one time it was almost small enough to understand and yet is not a "toy" operating system. Most of its internal algorithms were selected for *simplicity*, not for speed or sophistication. UNIX is readily available to departments of computer science, so many students may have access to it.

It might be best to have the students read the papers by Ritchie and Thompson [1974] and Thompson [1978] before reading this chapter.

■ Answers to Exercises

21.1 What are the major differences between 4.3BSD UNIX and SYSVR3? Is one system "better" than the other? Explain your answer.

Answer: 4.3BSD includes several features not found in SYSVR3, including long file names (up to 254 characters), the Berkeley File System (faster file access and more robust), symbolic links (soft pointers to files), processes having multiple access groups, and job control (easy per-job multiprocessing). SYSVR3 has Streams (a multilayered communications facility). Neither is "better" per se, but BSD does have more features.

21.2 How were the design goals of UNIX different from those of other operating systems during the early stages of UNIX development?

Answer: Rather than being a market-oriented operating system, like MULTICS, with definite goals and features, UNIX grew as a tool to allow Thompson and Ritchie to get their research done at Bell Labs. They found a spare PDP-11 system and wrote UNIX to help them with text-processing requirements. It therefore exactly suited their personal needs, not those of a company.

21.3 Why are there many different versions of UNIX currently available? In what ways is this diversity an advantage to UNIX? In what ways is it a disadvantage?

Answer: AT&T made the source code of UNIX available to universities and other sites, where experimentation and expansion took place. This allowed many people to have an influence on UNIX and to try out their own ideas. These ideas were circulated and the best ones were culled for inclusion in the standard varieties of UNIX. The disadvantage this causes is there is no "standard" version of UNIX. Programs written for UNIX may only run on one, or some, versions of UNIX, but rarely all.

21.4 What are the advantages and disadvantages of writing an operating system in a high-level language, such as C?

Answer: C makes UNIX highly portable, as evidenced by the many systems it runs on. It is also (arguably) faster to write and debug code in a high-level language, allowing UNIX to be modified more quickly than assembly-language-based operating systems. Of course it runs less efficiently than if it had been written in assembly language, like most other operating systems. It is generally larger than assembly-language operating systems too.

21.5 In what circumstances is the system-call sequence **fork execve** most appropriate? When is **vfork** preferable?

Answer: Since **vfork** is a fairly dangerous system call, it should only be used when a large process needs to be started. For small child processes, the **fork execve** call sequence is almost as efficient and does not allow its address space to be affected.

21.6 Does 4.3BSD UNIX give scheduling priority to I/O or CPU-bound processes? For what reason does it differentiate between these categories, and why is one given priority over the other? How does it know which of these categories fits a given process?

Answer: I/O-bound processes have priority. Since I/O-bound processes (like text editors) are more closely associated with a user, a better performance for I/O-bound processes give the users quicker response and makes the system seem "faster." UNIX tracks the number of input and output characters for each process, and which devices they are associated with. The more characters UNIX sees coming from tty devices, the more I/O-bound a process is.

21.7 Early UNIX systems used swapping for memory management, whereas 4.3BSD used paging and swapping. Discuss the advantages and disadvantages of the two memory methods.

Answer: When a CPU is slow, compared to its backing store, swapping makes sense. The CPU can issue one transfer command and the I/O system can move an entire process into or out of main memory. As CPUs get faster, paging makes more sense. The CPU has more time to decide which pages are not being used and to issue transfer requests. Paging generally requires "smarter" hardware, with access bits for each page of memory, or at least invalid page bits. Swapping wastes memory due to external fragmentation. Even on paging systems, swapping is useful when thrashing is occurring due to too many active processes touching too many pages.

21.8 Describe the modifications to a file system that the 4.3BSD kernel makes when a process requests the creation of a new file */tmp/foo* and writes to that file sequentially until the file size reaches 20K.

Answer: Let's assume that the block size is 4K. The kernel receives a *creat* or *open* system call (with the "create" flag set). It locates the directory in which the file is requested to be created and verifies that the process has write permission in that directory, and that no file exists with that same name without write permission. It locates the cylinder group that contains the directory, and finds a free inode in that cylinder group if there is room; if not, it does a “long seek” to a nearby group that has room.

It allocates the inode by removing it from the free inode list. It then modifies the free inode to show that it is used and updates all the appropriate fields (write date, size = 0, owner and group, protection, etc.). The system then creates a new directory entry in the parent directory’s data area that has the name of the new file and a pointer to its newly-allocated inode. The inode is then placed in the per-process table of open files and its file pointer is set to 0. The kernel’s file-structure table and the in-core inode list are updated too. The directory entry is then written to disk to assure that directories are always consistent.

The system then receives “write” system calls until 20K of data is received. If the caller is efficient, the writes will occur in 4K chunks (the size of a complete block). If this is the case, the system locates a free block in the cylinder group and changes the free block bit map to show the block is in use. It changes the inode such that the next free direct block is changed to have the value of the disk block. So the first write of 4K would allocate the first direct block, the second write the second block, and so on. These writes are buffered in the block buffer cache until the system deems it necessary to write them to disk.

If writes are done in other than 4K increments, the system must allocate fragments of 1K to handle any writes that do not end at a 4K increment. Each following write would require the system to copy the data in any fragments left by last write into a new block, and start appending the new data there. This is very efficient obviously (2 reads and a write per write). Fortunately the disk buffer cache alleviates some of this overhead by not writing data immediately to disk.

21.9 Directory blocks in 4.3BSD are written synchronously when they are changed. Consider what would happen if they were written asynchronously. Describe the state of the file system if a crash occurred after all the files in a directory were deleted but before the directory entry was updated on disk.

Answer: The contents of the file system and the description of that file system (the directory structure) would not correspond. In such a case points to invalid blocks, or blocks of another file, might result. The file system would be in a state of chaos and unusable.

21.10 Describe the process that is needed to recreate the free list after a crash in 4.1BSD.

Answer: No answer

21.11 What effects on system performance would the following changes to 4.3BSD have? Explain your answers.

a. The merging of the block buffer cache and the process paging space

b. Clustering disk I/O into larger chunks

c. Implementing and using shared memory to pass data between processes, rather than using RPC or sockets

d. Using the ISO seven-layer networking model, rather than the ARM network model

Answer:

a. Such a merge was done in SunOS 4.1. The result is a more general model of memory use. If lots of file transfers are occurring, more memory is used to hold data blocks. If more processes are executing, more storage is devoted to paging.

b. Another change to SunOS. This change resulted in more efficient use of the disks in the system — larger chunks of data are transferred with fewer seeks.

c. More efficient data transfer between communicating processes.

d. Less efficient network use, as a packet spends more time traversing the network protocol stack before and after being transmitted on the network.

21.12 What socket type should be used to implement an intercomputer file-transfer program? What type should be used for a program that periodically tests to see whether another computer is up on the network? Explain your answer.

Answer: Reliable delivered message would be best, because transfers are sure to occur but open connections are not needed between the systems. Datagrams are the next best, because they are unreliable. Perhaps streams are another choice if open connections are desired. Sun NFS uses datagrams because reliable delivered messages are not implemented. A datagram is about the only choice for testing the availability of other systems, since they may or may not be able to receive a packet (disallowing reliable delivered messages).

Chapter 22

THE LINUX SYSTEM

Chapter 21 discussed the internals of the 4.3BSD operating system in detail. BSD is just one of the UNIX-like systems. Linux is another UNIX-like system that has gained popularity in recent years. In this chapter, we look at the history and development of Linux, and cover the user and programmer interfaces that Linux presents—interfaces that owe a great deal to the UNIX tradition. We also discuss the internal methods by which Linux implements these interfaces. However, since Linux has been designed to run as many standard UNIX applications as possible, it has much in common with existing UNIX implementations. We do not duplicate the basic description of UNIX given in the previous chapter.

Linux is a rapidly evolving operating system. This chapter describes specifically the Linux 2.0 kernel, released in June 1996.

■ Answers to Exercises

22.1 Linux runs on a variety of hardware platforms. What steps must the Linux developers take to ensure that the system is portable to different processors and memory-management architectures, and to minimize the amount of architecture-specific kernel code?

Answer: The organization of architecture-dependent and architecture-independent code in the Linux kernel is designed to satisfy two design goals: to keep as much code as possible common between architectures, and to provide a clean way of defining architecture-specific properties and code. The solution must of course be consistent with the overriding aims of code maintainability and performance.

There are different levels of architecture dependence in the kernel, and different techniques are appropriate in each case to comply with the design requirements. These levels include:

CPU word size and endianness These are issues which affect the portability of all software written in C, but especially so for an operating system, where the size and alignment of data must be carefully arranged.

CPU process architecture Linux relies on many forms of hardware support for its process and memory management. Different processors have their own mechanisms for changing between protection domains (e.g., entering kernel mode from user mode), rescheduling processes, managing virtual memory and handling incoming interrupts.

The Linux kernel source code is organized so as to allow as much of the kernel as possible to be independent of the details of these architecture-specific features. To this end, the kernel keeps not one but two separate subdirectory hierarchies for each hardware architecture. One contains the code which is appropriate only for that architecture, including such functionality as the system call interface and low-level interrupt management code.

The second architecture-specific directory tree contains C header files which are descriptive of the architecture. These header files contain type definitions and macros designed to hide the differences between architectures. They provide standard types for obtaining words of a given length, macro constants defining such things as the architecture word size or page size, and function macros to perform common tasks such as converting a word to a given byte-order or doing standard manipulations to a page table entry.

Given these two architecture-specific subdirectory trees, a large portion of the Linux kernel can be made portable between architectures. An attention to detail is required: when a 32 bit integer is required, the programmer must use the explicit __int32 type rather than assume than an int is a given size, for example. However, as long as the architecture-specific header files are used, then most process and page-table manipulation can be performed using common code between the architectures. Code which definitely cannot be shared is kept safely detached from the main common kernel code.

22.2 Dynamically loadable kernel modules give flexibility when drivers are added to a system, but do they have disadvantages too? Under what circumstances would a kernel be compiled into a single binary file, and when would it be better to keep it split into modules? Explain your answer.

Answer: There are two principal drawbacks with the use of modules. The first is size: module management consumes unpagable kernel memory, and a basic kernel with a number of modules loaded will consume more memory than an equivalent kernel with the drivers compiled into the kernel image itself. This can be a very significant issue on machines with limited physical memory.

The second drawback is that modules can increase the complexity of the kernel bootstrap process. It is hard to load up a set of modules from disk if the driver needed to access that disk is itself a module which needs to be loaded. As a result, managing the kernel bootstrap with modules can require extra work on the part of the administrator: the modules required to bootstrap need to be placed into a ramdisk image which is loaded alongside the initial kernel image when the system is initialized.

There are certain cases where it is clearly better to use a modular kernel, and other cases where it is better to use a kernel with its device drivers prelinked. Where minimizing the size of the kernel is important, the choice will depend on how often the various device drivers are used. If they are in constant use, then modules are unsuitable. This is especially true where drivers are needed for the boot process itself. On the other hand, if some drivers are not always needed, then the module mechanism allows those drivers to be loaded and unloaded on demand, potentially offering a net saving in physical memory.

Where a kernel is to be built which must be usable on a large variety of very different machines, then building it with modules is clearly preferable to using a single kernel with dozens of unnecessary drivers consuming memory. This is particularly the case for commercially-distributed kernels, where supporting the widest variety of hardware in the simplest manner possible is a priority.

However, if a kernel is being built for a single machine whose configuration is known in advance, then compiling and using modules may simply be an unnecessary complexity. In cases like this, the use of modules may well be a matter of taste.

22.3 Multithreading is a commonly used programming technique. Describe three different ways that threads could be implemented. Explain how these ways compare to the Linux **clone** mechanism. When might each alternative mechanism be better or worse than using clones?

Answer: Thread implementations can be broadly classified into two groups: kernel-based threads and user-mode threads. User-mode thread packages rely on some kernel support—they may require timer interrupt facilities, for example—but the scheduling between threads is not performed by the kernel but by some library of user-mode code. Multiple threads in such an implementation appear to the operating system as a single execution context. When the multithreaded process is running, it decides for itself which of its threads to execute, using non-local jumps to switch between threads according to its own preemptive or non-preemptive scheduling rules.

Alternatively, the operating system kernel may provide support for threads itself. In this case, the threads may be implemented as separate processes which happen to share a complete or partial common address space, or they may be implemented as separate execution contexts within a single process. Whichever way the threads are organized, they appear as fully independent execution contexts to the application.

Hybrid implementations are also possible, where a large number of threads are made available to the application using a smaller number of kernel threads. Runnable user threads are run by the first available kernel thread.

In Linux, threads are implemented within the kernel by a clone mechanism which creates a new process within the same virtual address space as the parent process. Unlike some kernel-based thread packages, the Linux kernel does not make any distinction between threads and processes: a thread is simply a process which did not create a new virtual address space when it was initialized.

The main advantage of implementing threads in the kernel rather than in a user-mode library are that:

- kernel threaded systems can take advantage of multiple processors if they are available; and
- if one thread blocks in a kernel service routine (for example, a system call or page fault), other threads are still able to run.

Another lesser advantage is the ability to assign different security attributes to each thread.

User-mode implementations do not have these advantages. Because such implementations run entirely within a single kernel execution context, only one thread can ever be running at once, even if multiple CPUs are available. For the same reason, if one thread enters a system call, no other threads can run until that system call completes. As a result, one thread doing a blocking disk read will hold up every thread in the application. However, user-mode implementations do have their own advantages. The most obvious is performance: invoking the kernel's own scheduler to switch between threads involves entering a new protection domain as the CPU switches to kernel mode, whereas switching between threads in user-mode can be achieved simply by saving and restoring the main CPU registers. User-mode threads may also consume less system memory: most UNIX systems will reserve at least a full page for a kernel stack for each kernel thread, and this stack may not be pageable.

The hybrid approach, implementing multiple user threads over a smaller number of kernel threads, allows a balance between these tradeoffs to be achieved. The kernel threads will allow multiple threads to be in blocking kernel calls at once and will permit running on multiple CPUs, and user-mode thread switching can occur within each kernel thread to perform lightweight threading without the overheads of having too many kernel threads. The downside of this approach is complexity: giving control over the tradeoff complicates the thread library's user interface.

22.4 What are the extra costs incurred by the creation and scheduling of a process, as compared to the cost of a cloned thread?

Answer: In Linux, creation of a thread involves only the creation of some very simple data structures to describe the new thread. Space must be reserved for the new thread's execution context—its saved registers, its kernel stack page and dynamic information such as its security profile and signal state—but no new virtual address space is created.

Creating this new virtual address space is the most expensive part of the creation of a new process. The entire page table of the parent process must be copied, with each page being examined so that copy-on-write semantics can be achieved and so that reference counts to physical pages can be updated. The parent process's virtual memory is also affected by the process creation: any private read / write pages owned by the parent must be marked read-only so that copy-on-write can happen (copy-on-write relies on a page fault being generated when a write to the page occurs).

Scheduling of threads and processes also differs in this respect. The decision algorithm performed when deciding what process to run next is the same regardless of whether the process is a fully independent process or just a thread, but the action of context-switching to a separate process is must more costly than switching to a thread. A process requires that the CPU's virtual memory control registers be updated to point to the new virtual address space's page tables.

In both cases—creation of a process or context switching between processes—the extra virtual memory operations have a significant cost. On many CPUs, changing page tables or swapping between page tables is not cheap: all or part of the virtual address translation look-aside buffers in the CPU must be purged when the page tables are changed. These costs are not incurred when creating or scheduling between threads.

22.5 The Linux scheduler implements *soft* real-time scheduling. What features are missing that are necessary for some real-time programming tasks? How might they be added to the kernel?

Answer: Linux's "soft" real-time scheduling provides ordering guarantees concerning the priorities of runnable processes: real-time processes will always be given a higher priority by the scheduler than normal time-sharing processes, and a real-time process will never be interrupted by another process with a lower real-time priority.

However, the Linux kernel does not support "hard" real-time functionality. That is, when a process is executing a kernel service routine, that routine will always execute to completion unless it yields control back to the scheduler either explicitly or implicitly (by waiting for some asynchronous event). There is no support for preemptive scheduling of kernel-mode processes. As a result, any kernel system call which runs for a significant amount of time without rescheduling will block execution of any real-time processes.

Many real-time applications require such hard real-time scheduling. In particular, they often require guaranteed worst-case response times to external events. To achieve these guarantees, and to give user-mode real time processes a true higher priority than kernel-mode lower-priority processes, it is necessary to find a way to avoid having to wait for low-priority kernel calls to complete before scheduling a real-time process. For example, if a device driver generates an interrupt which wakes up a high priority real-time process, then the kernel needs to be able to schedule that process as soon as possible, even if some other process is already executing in kernel mode.

Such preemptive rescheduling of kernel-mode routines comes at a cost. If the kernel cannot rely on non-preemption to ensure atomic updates of shared data structures, then reads of or updates to those structures must be protected by some other, finer-granularity locking mechanism. This fine-grained locking of kernel resources is the main requirement for provision of tight scheduling guarantees.

Many other kernel features could be added to support real-time programming. Deadline-based scheduling could be achieved by making modifications to the scheduler. Prioritization of IO operations could be implemented in the block-device IO request layer.

22.6 The Linux kernel does not allow paging out of kernel memory. What effect does this restriction have on the kernel's design? What are two advantages and two disadvantages of this design decision?

Answer: The primary impact of disallowing paging of kernel memory in Linux is that the non-preemptability of the kernel is preserved. Any process taking a page fault, whether in kernel or in user mode, risks being rescheduled while the required data is paged in from disk. Because the kernel can rely on not being rescheduled during access to its primary data structures, locking requirements to protect the integrity of those data structures are very greatly simplified. Although design simplicity is a benefit in itself, it also provides an important performance advantage on uni-processor machines due to the fact that it is not necessary to do additional locking on most internal data structures.

There are a number of disadvantages to the lack of pageable kernel memory, however. First of all, it imposes constraints on the amount of memory that the kernel can use. It is unreasonable to keep very large data structures in non-pageable memory, since that represents physical memory which absolutely cannot be used for anything else. This has two impacts: first of all, the kernel must prune back many of its internal data structures manually, instead of being able to rely on a single virtual memory mechanism to keep physical memory usage under control. Secondly, it makes it infeasible to implement certain features which require very large amounts of virtual memory in the kernel, such as the /tmp-filesystem (a fast virtual-memory based filesystem found on some UNIX systems).

Note that the complexity of managing page faults while running kernel code is not an issue here. The Linux kernel code is already able to deal with page faults: it needs to be able to deal with system calls whose arguments reference user memory which may be paged out to disk.

22.7 In Linux, shared libraries perform many operations central to the operating system. What is the advantage of keeping this functionality out of the kernel? Are there any drawbacks? Explain your answer.

Answer: There are a number of reasons for keeping functionality in shared libraries rather than in the kernel itself. These include:

Reliability. Kernel-mode programming is inherently higher risk than user-mode programming. If the kernel is coded correctly so that protection between processes is enforced, then an occurrence of a bug in a user-mode library is likely to affect only the currently executing process, whereas a similar bug in the kernel could conceivably bring down the entire operating system.

Performance. Keeping as much functionality as possible in user-mode shared libraries helps performance in two ways. First of all, it reduces physical memory consumption: kernel memory is non-pageable, so every kernel function is permanently resident in physical memory, but a library function can be paged in from disk on demand and does not need to be physically present all of the time. Although the library function may be resident in many processes at once, page sharing by the virtual memory system means that it is only loaded into physical memory at most once.

Secondly, calling a function in a loaded library is a very fast operation, but calling a kernel function through a kernel system service call is much more expensive. Entering the kernel involves changing the CPU protection domain, and once in the kernel, all of the arguments supplied by the process must be very carefully checked for correctness: the kernel cannot afford to make any assumptions about the validity of the arguments passed in, whereas a library function might reasonably do so. Both of these factors make calling a kernel function much slower than calling the same function in a library.

Manageability. Many different shared libraries can be loaded by an application. If new functionality is required in a running system, shared libraries to provide that functionality can be installed without interrupting any already-running processes. Similarly, existing shared libraries can generally be upgraded without requiring any system down-time. Unprivileged users can create shared libraries to be run by their own programs. All of these attributes make shared libraries generally easier to manage than kernel code.

There are, however, a few disadvantages to having code in a shared library. There are obvious examples of code which is completely unsuitable for implementation in a library, including low-level functionality such as device drivers or filesystems. In general, services shared around the entire system are better implemented in the kernel if they are performance-critical, since the alternative—running the shared service in a separate process and communicating with it through inter-process communication—requires two context switches for every service requested by a process. In some cases it may be appropriate to prototype a service in user-mode but implement the final version as a kernel routine.

Security is also an issue. A shared library runs with the privileges of the process calling the library. It cannot directly access any resources inaccessible to the calling process, and the calling process has full access to all of the data structures maintained by the shared library. If the service being provided requires any privileges outside of a normal process's, or if the data managed by the library needs to be protected from normal user processes, then libraries are inappropriate, and a separate server process (if performance permits) or a kernel implementation is required.

22.8 What are three advantages of dynamic (shared) linkage of libraries compared to static linkage? What are two cases where static linkage is preferable.

Answer: The primary advantages of shared libraries are that they reduce the memory and disk space used by a system, and they enhance maintainability.

When shared libraries are being used by all running programs, there is only one instance of each system library routine on disk, and at most one instance in physical memory. When the library in question is one used by many applications and programs, then the disk and memory savings can be quite substantial. In addition, the startup time for running new programs can be reduced, since many of the common functions needed by that program are likely to be already loaded into physical memory.

Maintainability is also a major advantage of dynamic linkage over static. If all running programs use a shared library to access their system library routines, then upgrading those routines, either to add new functionality or to fix bugs, can be done simply by replacing that shared library. There is no need to recompile or relink any applications; any programs loaded after the upgrade is complete will automatically pick up the new versions of the libraries.

There are other advantages too. A program which uses shared libraries can often be adapted for specific purposes simply by replacing one or more of its libraries, or even (if the system allows it, and most UNIXs—including Linux—do) adding a new one at run time. For example, a debugging library can be substituted for a normal one to trace a problem in an application. Shared libraries also allow program binaries to be linked against commercial, proprietary library code without actually including any of that code in the program's final executable file. This is important because on most UNIX systems, many of the standard shared libraries are proprietary, and there may be licensing issues which prevent including that code in executable files to be distributed to third parties.

There are, however, places where static linkage is appropriate. One example is in rescue environments for system administrators. If a system administrator makes a mistake while installing any new libraries, or if hardware develops problems, it is quite possible for the existing shared libraries to become corrupt. As a result, it is common for a basic set of rescue utilities to be linked statically, so that there is an opportunity to correct the fault without having to rely on the shared libraries functioning correctly.

There are also performance advantages which sometimes make static linkage preferable in special cases. For a start, dynamic linkage does increase the startup time for a program, as the linking must now be done at run-time rather than at compile-time. Dynamic linkage can also sometimes increase the maximum working set size of a program (the total number of physical pages of memory required to run the program). In a shared library, the user has no control over where in the library binary file the various functions reside. Since most functions do not precisely fill a full page or pages of the library, loading a function will usually result in loading in parts of the surrounding functions, too. With static linkage, absolutely no functions which are not referenced (directly or indirectly) by the application need to be loaded into memory.

Other issues surrounding static linkage include ease of distribution: it is easier to distribute an executable file with static linkage than with dynamic linkage if the distributor is not certain whether the recipient will have the correct libraries installed in advance. There may also be commercial restrictions against redistributing some binaries as shared libraries: for example, the license for the UNIX "Motif" graphical environment allows binaries using Motif to be distributed freely as long as they are statically linked, but the shared libraries may not be used without a license.

22.9 Compare the use of networking sockets with the use of shared memory as a mechanism for communicating data between processes on a single computer. What are the advantages of each method? When might each be preferred?

Answer: There are a number of advantages in using network sockets rather than shared memory for local communication. The main advantage is that the socket programming interface features a rich set of synchronization features. A process can easily determine when new data has arrived on a socket connection, how much data is present, and who sent it. Processes can block until new data arrives on a socket, or can request that a signal be delivered when data arrives. A socket also manages separate connections. A process with a socket open for receive can accept multiple connections to that socket, and will be told when new processes try to connect or when old processes drop their connections.

Shared memory offers none of these features. There is no way for a process to determine whether another process has delivered or changed data in shared memory other than by going to look at the contents of that memory. It is impossible for a process to block and request a wakeup when shared memory is delivered, and there is no standard mechanism for other processes to establish a shared memory link to an existing process.

However, shared memory has the advantage that it is very much faster than socket communications in many cases. When data is sent over a socket, it is typically copied from memory to memory multiple times. Shared memory updates require no data copies: if one process updates a data structure in shared memory, that update is immediately visible to all other processes sharing that memory. Sending or receiving data over a socket requires that a kernel system service call be made to initiate the transfer, but shared memory communication can be performed entirely in user mode with no transfer of control required.

Socket communication is typically preferred when connection management is important, or when there is a requirement to synchronize the sender and receiver. For example, server processes will usually establish a listening socket to which clients can connect when they want to use that service. Once the socket is established, individual requests are also sent using the socket, so that the server can easily determine when a new request arrives and who it arrived from.

However, there are cases when shared memory is preferred. Shared memory is often a better solution when either large amounts of data are to be transferred, or when two processes need random access to a large common data set. In this case, however, the communicating process may still need an extra mechanism in addition to shared memory to achieve synchronization between themselves. The X Window System, a graphical display environment for UNIX, is a good example of this: most graphic requests are sent over sockets, but shared memory is offered as an additional transport in special cases where large bitmaps are to be displayed on the screen. In this case, a request to display the bitmap will still be sent over the socket, but the bulk data of the bitmap itself will be sent via shared memory.

22.10 UNIX systems used to use disk-layout optimizations based on the rotation position of disk data, but modern implementations, including Linux, simply optimize for sequential data access. Why do they do so? Of what hardware characteristics does sequential access take advantage? Why is rotational optimization no longer so useful?

Answer: The performance characteristics of disk hardware has changed substantially in recent years. In particular, many enhancements have been introduced to increase the maximum bandwidth that can be achieved on a disk. In a modern system, there can be a long pipeline between the operating system and the disk's read-write head. A disk I/O request has to pass through the computer's local disk controller, over bus logic to the disk drive itself, and then internally to the disk where there is likely to be a complex controller which can cache data accesses and potentially optimize the order of I/O requests.

Because of this complexity, the time taken for one I/O request to be acknowledged and for the next request to be generated and received by the disk can far exceed the amount of time between one disk sector passing under the read-write head and the next sector header arriving. In order to be able to efficiently read multiple sectors at once, disks will employ a readahead cache. While one sector is being passed back to the host computer, the disk will be busy reading the next sectors in anticipation of a request to read them. If read requests start arriving in an order which breaks this readahead pipeline, performance will drop. As a result, performance benefits substantially if the operating system tries to keep I/O requests in strict sequential order.

A second feature of modern disks is that their geometry can be very complex. The number of sectors per cylinder can vary according to the position of the cylinder: more data can be squeezed into the longer tracks nearer the edge of the disk than at the center of the disk. For an operating system to optimize the rotational position of data on such disks, it would have to have complete understanding of this geometry, and of the timing characteristics of the disk and its controller. In general, only the disk's internal logic can determine the optimal scheduling of I/Os, and the disk's geometry is likely to defeat any attempt by the operating system to perform rotational optimizations.

22.11 The Linux source code is freely and widely available over the Internet or from CD-Rom vendors. What are three implications of this availability on the security of the Linux system?

Answer: The open availability of an operating system's source code has both positive and negative impacts on security, and it is probably a mistake to say that it is definitely a good thing or a bad thing.

Linux's source code is open to scrutiny by both the good guys and the bad guys. In its favor, this has resulted in the code being inspected by a large number of people who are concerned about security and who have eliminated any vulnerabilities they have found.

On the other hand is the "security through obscurity" argument, which states that attackers' jobs are made easier if they have access to the source code of the system they are trying to penetrate. By denying attackers information about a system, the hope is that it will be harder for those attackers to find and exploit any security weaknesses which may be present.

In other words, open source code implies both that security weaknesses can be found and fixed faster by the Linux community, increasing the security of the system; and that attackers can more easily find any weaknesses that do remain in Linux.

There are other implications for source code availability, however. One is that if a weakness in Linux is found and exploited, then a fix for that problem can be created and distributed very quickly. (Typically, security problems in Linux tend to have fixes available to the public within 24 hours of their discovery.) Another is that if security is a major concern to particular users, then it is possible for those users to review the source code to satisfy themselves of its level of security or to make any changes that they wish to add new security measures.

Chapter 23

WINDOWS / NT

The Windows NT operating system is designed to take advantage of the many advances in processor technology. Although primarily run on the Intel architecture, NT was designed to be portable in order to take advantage of whatever promising technologies happened to come along. Key goals for the system included portability, security, POSIX compliance, multiprocessor support, extensibility, international support, and compatibility with MS-DOS and MS-Windows applications. Windows NT is similar to Mach in that it is a microkernel based operating system which results in a stable base operating system and allows enhancements to be made to one part of the operating system without changing any of the other parts.

■ Answers to Exercises

23.1 Discuss why moving the graphics code in NT from user mode to kernel mode would decrease the reliability of the system. How does this violate the original design goals for NT?

Answer: The code was moved to eliminate the overhead of interprocess communication. The advantage of the previous method of having the code in the Win32 subsystem is that the kernel / executive as well as other subsystems are protected from an error in the Win32 subsystem. The new method, while offering a performance increase to meet marketplace concerns, has the drawback that bad graphics code can bring down the entire system. Indeed, examples of this were seen posted on the internet. The design goal that was violated was that of independent subsystems that would not be able to affect other subsystems or the kernel. This was brought about by complaints from users of the older 16-bit windows versions who felt that applications ran slower on NT.

23.2 The NT VM manager uses a two-stage process to allocate memory. Why is this approach beneficial?

Answer: A process in NT is limited to 2 GB address space for data. The two-stage process allows the access of much larger datasets, by reserving space in the processes address space first and then committing the storage to a memory mapped file. An application could thus window through a large database (by changing the committed section) without exceeding process quotas or utilizing a huge amount of physical memory.

23.3 Discuss the advantages and disadvantages of the particular page-table structure in NT.
Answer: Each process has its own page directory that requires about 4 MB of storage. Since it is a 3 level design, this means that there could be up to 3 page faults just accessing a virtual address. Shared memory adds one more level. The page faults can occur because NT does not commit the required memory (the 4 MB) until necessary. Since each process has its own page directory, there is no way for processes to share virtual addresses. The prototype page table entry adds a level of indirection, but eliminates the update of multiple page table entries for shared pages.

23.4 What is the maximum number of page faults that could occur in the access of a virtual address, and of a shared virtual address? What hardware mechanism is provided by most processors to decrease these numbers?
Answer: 4 for shared addresses. 3 for others. Translation Lookaside Buffers.

23.5 What is the purpose of a prototype page-table entry in NT?
Answer: The prototype page-table entry is used to point to shared pages instead of having multiple page-table entries point to the same page. It adds another layer of indirection, but saves having to update *N* page-table entries.

23.6 What steps must the cache manager take to copy data into and out of the cache?
Answer: Please see Section 23.3.3.6 for details.

23.7 What are the problems involved in running 16-bit Windows applications in a VDM? What are the solutions chosen by NT? What are the drawbacks of these solutions?
Answer: No answer.

23.8 What changes would be needed for NT to run a process that uses a 64-bit address space?
Answer: Primarily, the VM Manager would have to be extensively modified. This might entail changing the page size, adding another level to the page table structure, etc. It may be impractical to support the full 64-bit address range. Indeed, the “64-bit” version of NT, NT Server/E 5.0, will support a maximum of 32 megabytes of RAM. For another approach, see the August 1997 Oracle White Paper entitled ”Oracle Very Large Memory (VLM) for Digital Alpha NT.”

23.9 NT has a centralized cache manager. What are the advantages and disadvantages of this cache manager?
Answer: One of the major advantages is that each file system doesn’t have to provide its own caching. Also, the cache manager is tightly coupled to the VM manager. The drawback is that some devices want to do DMA tranfers. Also different caching schemes might be able to save the data copying that is present with the NT scheme.

23.10 NT uses a packet-driven I/O system. Discuss the pros and cons of the packet-driven approach to I/O.
Answer: The standard form of the packet makes it easier to write drivers since they can follow a standard interface and processing hierarchy. A major con is that all the packet copying leads to inefficiencies, although it seems that many TCP/IP stacks have the same problem.

23.11 Consider a main-memory database of 1 TB. What mechanisms in NT could be used to access it?
Answer: See Question 23.2.