

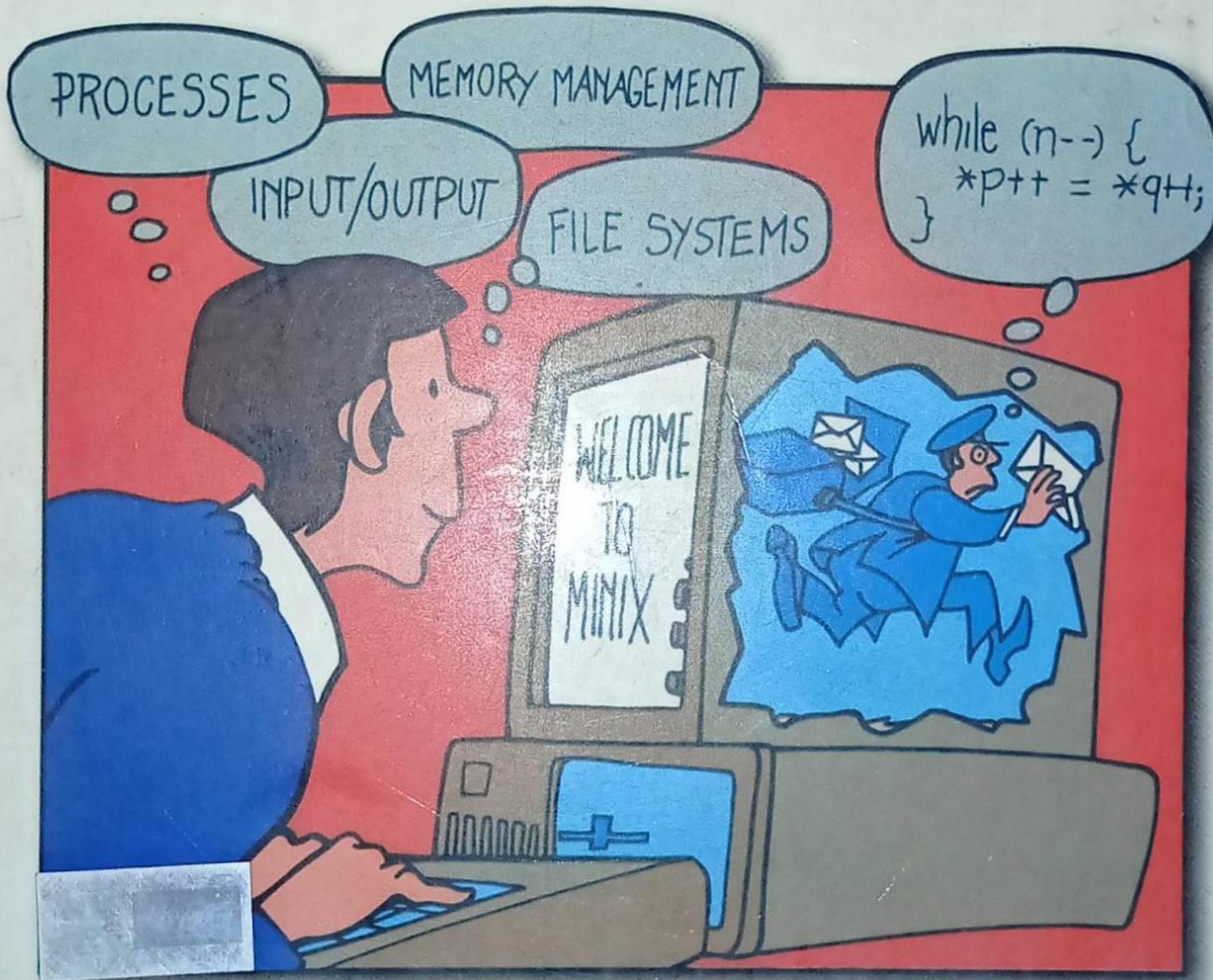
LOW PRICE EDITION

PEARSON  
Education

*Second Edition*

# OPERATING SYSTEMS

*Design and Implementation*



**ANDREW S. TANENBAUM  
ALBERT S. WOODHULL**

# CONTENTS

## PREFACE

xv

<b>1</b>	<b>INTRODUCTION</b>	<b>1</b>
1.1	WHAT IS AN OPERATING SYSTEM? 3	
1.1.1	The Operating System as an Extended Machine 3	
1.1.2	The Operating System as a Resource Manager 4	
1.2	HISTORY OF OPERATING SYSTEMS 5	
1.2.1	The First Generation (1945–55) Vacuum Tubes and Plugboards 6	
1.2.2	The Second Generation (1955–65) Transistors and Batch Systems 6	
1.2.3	The Third Generation (1965–1980): ICs and Multiprogramming 8	
1.2.4	The Fourth Generation (1980–Present): Personal Computers 12	
1.2.5	History of MINIX 13	
1.3	OPERATING SYSTEM CONCEPTS 15	
1.3.1	Processes 15	
1.3.2	Files 17	
1.3.3	The Shell 20	
1.4	SYSTEM CALLS 21	
1.4.1	System Calls for Process Management 22	
1.4.2	System Calls for Signaling 26	
1.4.3	System Calls for File Management 28	
1.4.4	System Calls for Directory Management 33	
1.4.5	System Calls for Protection 35	
1.4.6	System Calls for Time Management 36	

1.5	OPERATING SYSTEM STRUCTURE	37
1.5.1	Monolithic Systems	37
1.5.2	Layered Systems	39
1.5.3	Virtual Machines	40
1.5.4	Client-Server Model	42
1.6	OUTLINE OF THE REST OF THIS BOOK	44
1.7	SUMMARY	44

## 2 PROCESSES

47

2.1	INTRODUCTION TO PROCESSES	47
2.1.1	The Process Model	48
2.1.2	Implementation of Processes	52
2.1.3	Threads	53
2.2	INTERPROCESS COMMUNICATION	57
2.2.1	Race Conditions	57
2.2.2	Critical Sections	58
2.2.3	Mutual Exclusion with Busy Waiting	59
2.2.4	Sleep and Wakeup	63
2.2.5	Semaphores	66
2.2.6	Monitors	68
2.2.7	Message Passing	72
2.3	CLASSICAL IPC PROBLEMS	75
2.3.1	The Dining Philosophers Problem	75
2.3.2	The Readers and Writers Problem	77
2.3.3	The Sleeping Barber Problem	80
2.4	PROCESS SCHEDULING	82
2.4.1	Round Robin Scheduling	84
2.4.2	Priority Scheduling	85
2.4.3	Multiple Queues	86
2.4.4	Shortest Job First	87
2.4.5	Guaranteed Scheduling	89
2.4.6	Lottery Scheduling	89
2.4.7	Real-Time Scheduling	90
2.4.8	Two-level Scheduling	92
2.4.9	Policy versus Mechanism	93

2.5	OVERVIEW OF PROCESSES IN MINIX	93
2.5.1	The Internal Structure of MINIX	93
2.5.2	Process Management in MINIX	95
2.5.3	Interprocess Communication in MINIX	97
2.5.4	Process Scheduling in MINIX	98
2.6	IMPLEMENTATION OF PROCESSES IN MINIX	98
2.6.1	Organization of the MINIX Source Code	99
2.6.2	The Common Header Files	102
2.6.3	The MINIX Header Files	107
2.6.4	Process Data Structures and Header Files	112
2.6.5	Bootstrapping MINIX	120
2.6.6	System Initialization	122
2.6.7	Interrupt Handling in MINIX	128
2.6.8	Interprocess Communication in MINIX	137
2.6.9	Scheduling in MINIX	140
2.6.10	Hardware-Dependent Kernel Support	142
2.6.11	Utilities and the Kernel Library	145
2.7	SUMMARY	147

## 3 INPUT/OUTPUT 153

3.1	PRINCIPLES OF I/O HARDWARE	154
3.1.1	I/O Devices	154
3.1.2	Device Controllers	155
3.1.3	Direct Memory Access (DMA)	157
3.2	PRINCIPLES OF I/O SOFTWARE	159
3.2.1	Goals of the I/O Software	159
3.2.2	Interrupt Handlers	161
3.2.3	Device Drivers	161
3.2.4	Device-Independent I/O Software	162
3.2.5	User-Space I/O Software	164
3.3	DEADLOCKS	166
3.3.1	Resources	167
3.3.2	Principles of Deadlock	168
3.3.3	The Ostrich Algorithm	170
3.3.4	Detection and Recovery	172
3.3.5	Deadlock Prevention	173
3.3.6	Deadlock Avoidance	175

## CONTENTS

x

3.4	OVERVIEW OF I/O IN MINIX	179
3.4.1	Interrupt Handlers in MINIX	180
3.4.2	Device Drivers in MINIX	181
3.4.3	Device-Independent I/O Software in MINIX	185
3.4.4	User-level I/O Software in MINIX	185
3.4.5	Deadlock Handling in MINIX	186
3.5	BLOCK DEVICES IN MINIX	187
3.5.1	Overview of Block Device Drivers in MINIX	187
3.5.2	Common Block Device Driver Software	190
3.5.3	The Driver Library	193
3.6	RAM DISKS	195
3.6.1	RAM Disk Hardware and Software	196
3.6.2	Overview of the RAM Disk Driver in MINIX	197
3.6.3	Implementation of the RAM Disk Driver in MINIX	198
3.7	DISKS	200
3.7.1	Disk Hardware	200
3.7.2	Disk Software	202
3.7.3	Overview of the Hard Disk Driver in MINIX	208
3.7.4	Implementation of the Hard Disk Driver in MINIX	211
3.7.5	Floppy Disk Handling	220
3.8	CLOCKS	222
3.8.1	Clock Hardware	223
3.8.2	Clock Software	224
3.8.3	Overview of the Clock Driver in MINIX	227
3.8.4	Implementation of the Clock Driver in MINIX	230
3.9	TERMINALS	235
3.9.1	Terminal Hardware	235
3.9.2	Terminal Software	240
3.9.3	Overview of the Terminal Driver in MINIX	249
3.9.4	Implementation of the Device-Independent Terminal Driver	264
3.9.5	Implementation of the Keyboard Driver	282
3.9.6	Implementation of the Display Driver	288
3.10	THE SYSTEM TASK IN MINIX	296
3.11	SUMMARY	304

**4 MEMORY MANAGEMENT** 309

- 4.1 BASIC MEMORY MANAGEMENT 310
  - 4.1.1 Monoprogramming without Swapping or Paging 310
  - 4.1.2 Multiprogramming with Fixed Partitions 311
- 4.2 SWAPPING 313
  - 4.2.1 Memory Management with Bit Maps 316
  - 4.2.2 Memory Management with Linked Lists 317
- 4.3 VIRTUAL MEMORY 319
  - 4.3.1 Paging 319
  - 4.3.2 Page Tables 322
  - 4.3.3 TLBs—Translation Lookaside Buffers 327
  - 4.3.4 Inverted Page Tables 330
- 4.4 PAGE REPLACEMENT ALGORITHMS 331
  - 4.4.1 The Optimal Page Replacement Algorithm 331
  - 4.4.2 The Not-Recently-Used Page Replacement Algorithm 332
  - 4.4.3 The First-In, First-Out (FIFO) Page Replacement Algorithm 333
  - 4.4.4 The Second Chance Page Replacement Algorithm 333
  - 4.4.5 The Clock Page Replacement Algorithm 334
  - 4.4.6 The Least Recently Used (LRU) Page Replacement Algorithm 334
  - 4.4.7 Simulating LRU in Software 336
- 4.5 DESIGN ISSUES FOR PAGING SYSTEMS 338
  - 4.5.1 The Working Set Model 338
  - 4.5.2 Local versus Global Allocation Policies 339
  - 4.5.3 Page Size 341
  - 4.5.4 Virtual Memory Interface 343
- 4.6 SEGMENTATION 343
  - 4.6.1 Implementation of Pure Segmentation 347
  - 4.6.2 Segmentation with Paging: MULTICS 348
  - 4.6.3 Segmentation with Paging: The Intel Pentium 352
- 4.7 OVERVIEW OF MEMORY MANAGEMENT IN MINIX 356
  - 4.7.1 Memory Layout 358
  - 4.7.2 Message Handling 361
  - 4.7.3 Memory Manager Data Structures and Algorithms 363
  - 4.7.4 The FORK, EXIT, and WAIT System Calls 367
  - 4.7.5 The EXEC System Call 368
  - 4.7.6 The BRK System Call 371
  - 4.7.7 Signal Handling 372
  - 4.7.8 Other System Calls 378

4.8	IMPLEMENTATION OF MEMORY MANAGEMENT IN MINIX	379
4.8.1	The Header Files and Data Structures	379
4.8.2	The Main Program	382
4.8.3	Implementation of FORK, EXIT, and WAIT	382
4.8.4	Implementation of EXEC	385
4.8.5	Implementation of BRK	386
4.8.6	Implementation of Signal Handling	387
4.8.7	Implementation of the Other System Calls	393
4.8.8	Memory Manager Utilities	394
4.9	SUMMARY	396

## 5 FILE SYSTEMS

401

5.1	FILES	402
5.1.1	File Naming	402
5.1.2	File Structure	404
5.1.3	File Types	405
5.1.4	File Access	407
5.1.5	File Attributes	408
5.1.6	File Operations	409
5.2	DIRECTORIES	410
5.2.1	Hierarchical Directory Systems	411
5.2.2	Path Names	412
5.2.3	Directory Operations	414
5.3	FILE SYSTEM IMPLEMENTATION	415
5.3.1	Implementing Files	415
5.3.2	Implementing Directories	419
5.3.3	Disk Space Management	422
5.3.4	File System Reliability	424
5.3.5	File System Performance	429
5.3.6	Log-Structured File Systems	432
5.4	SECURITY	434
5.4.1	The Security Environment	434
5.4.2	Famous Security Flaws	436
5.4.3	Generic Security Attacks	439
5.4.4	Design Principles for Security	441
5.4.5	User Authentication	442

5.5	PROTECTION MECHANISMS	446
5.5.1	Protection Domains	446
5.5.2	Access Control Lists	448
5.5.3	Capabilities	450
5.5.4	Covert Channels	451
5.6	OVERVIEW OF THE MINIX FILE SYSTEM	453
5.6.1	Messages	454
5.6.2	File System Layout	454
5.6.3	Bit Maps	458
5.6.4	I-nodes	460
5.6.5	The Block Cache	461
5.6.6	Directories and Paths	463
5.6.7	File Descriptors	465
5.6.8	File Locking	467
5.6.9	Pipes and Special Files	467
5.6.10	An Example: The READ System Call	469
5.7	IMPLEMENTATION OF THE MINIX FILE SYSTEM	470
5.7.1	Header Files and Global Data Structures	470
5.7.2	Table Management	474
5.7.3	The Main Program	482
5.7.4	Operations on Individual Files	485
5.7.5	Directories and Paths	493
5.7.6	Other System Calls	498
5.7.7	The I/O Device Interface	501
5.7.8	General Utilities	503
5.8	SUMMARY	503

## 6 READING LIST AND BIBLIOGRAPHY 507

6.1	SUGGESTIONS FOR FURTHER READING	507
6.1.1	Introduction and General Works	507
6.1.2	Processes	509
6.1.3	Input/Output	510
6.1.4	Memory Management	511
6.1.5	File Systems	511
6.2	ALPHABETICAL BIBLIOGRAPHY	512

CONTENTS

xiv

APPENDICES

A MINIX SOURCE CODE LISTING

521

B INDEX TO FILES

905

C INDEX TO SYMBOLS

909

INDEX

925