

THE **LINUX** PROGRAMMING INTERFACE

A Linux and UNIX® System Programming Handbook

MICHAEL KERRISK



THE LINUX PROGRAMMING INTERFACE

A Linux and UNIX® System Programming Handbook

MICHAEL KERRISK



**no starch
press**

San Francisco

THE LINUX PROGRAMMING INTERFACE. Copyright © 2010 by Michael Kerrisk.

All rights reserved. No part of this work may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or by any information storage or retrieval system, without the prior written permission of the copyright owner and the publisher.

14 13 12 11 10 1 2 3 4 5 6 7 8 9

ISBN-10: 1-59327-220-0

ISBN-13: 978-1-59327-220-3

Publisher: William Pollock

Production Editor: Riley Hoffman

Cover Design: Octopod Studios

Front Cover Photo: Rob Suisted

Back Cover Photo: Lynley Cook

Copyeditor: Marilyn Smith

Compositor: Susan Glinert Stevens

Proofreader: Linda Seifert

For technical reviewers, please refer to the author's acknowledgements

For information on book distributors or translations, please contact No Starch Press, Inc. directly:

No Starch Press, Inc.

38 Ringold Street, San Francisco, CA 94103

phone: 415.863.9900; fax: 415.863.9950; info@nostarch.com; www.nostarch.com

Library of Congress Cataloging-in-Publication Data

Kerrisk, Michael, 1961-

The Linux programming interface : a Linux and UNIX system programming handbook / by Michael Kerrisk.
p. cm.

Includes bibliographical references and index.

ISBN-13: 978-1-59327-220-3 (hardcover)

ISBN-10: 1-59327-220-0 (hardcover)

1. Linux. 2. UNIX (Computer file) 3. Operating systems (Computers) I. Title.

QA76.76.063K496 2010

005.4'32--dc22

2010001947

No Starch Press and the No Starch Press logo are registered trademarks of No Starch Press, Inc. Other product and company names mentioned herein may be the trademarks of their respective owners. Rather than use a trademark symbol with every occurrence of a trademarked name, we are using the names only in an editorial fashion and to the benefit of the trademark owner, with no intention of infringement of the trademark.

UNIX® is a registered trademark of The Open Group.

The information in this book is distributed on an “As Is” basis, without warranty. While every precaution has been taken in the preparation of this work, neither the author nor No Starch Press, Inc. shall have any liability to any person or entity with respect to any loss or damage caused or alleged to be caused directly or indirectly by the information contained in it.

This logo applies only to the text stock.

BRIEF CONTENTS

Preface	xxxi
Chapter 1: History and Standards	1
Chapter 2: Fundamental Concepts	21
Chapter 3: System Programming Concepts	43
Chapter 4: File I/O: The Universal I/O Model	69
Chapter 5: File I/O: Further Details	89
Chapter 6: Processes	113
Chapter 7: Memory Allocation	139
Chapter 8: Users and Groups	153
Chapter 9: Process Credentials	167
Chapter 10: Time	185
Chapter 11: System Limits and Options	211
Chapter 12: System and Process Information	223
Chapter 13: File I/O Buffering	233
Chapter 14: File Systems	251
Chapter 15: File Attributes	279
Chapter 16: Extended Attributes	311
Chapter 17: Access Control Lists	319
Chapter 18: Directories and Links	339
Chapter 19: Monitoring File Events	375

Chapter 20: Signals: Fundamental Concepts	387
Chapter 21: Signals: Signal Handlers.....	421
Chapter 22: Signals: Advanced Features	447
Chapter 23: Timers and Sleeping.....	479
Chapter 24: Process Creation.....	513
Chapter 25: Process Termination.....	531
Chapter 26: Monitoring Child Processes	541
Chapter 27: Program Execution	563
Chapter 28: Process Creation and Program Execution in More Detail.....	591
Chapter 29: Threads: Introduction.....	617
Chapter 30: Threads: Thread Synchronization	631
Chapter 31: Threads: Thread Safety and Per-Thread Storage.....	655
Chapter 32: Threads: Thread Cancellation	671
Chapter 33: Threads: Further Details	681
Chapter 34: Process Groups, Sessions, and Job Control	699
Chapter 35: Process Priorities and Scheduling	733
Chapter 36: Process Resources	753
Chapter 37: Daemons	767
Chapter 38: Writing Secure Privileged Programs	783
Chapter 39: Capabilities	797
Chapter 40: Login Accounting	817
Chapter 41: Fundamentals of Shared Libraries	833
Chapter 42: Advanced Features of Shared Libraries.....	859
Chapter 43: Interprocess Communication Overview	877
Chapter 44: Pipes and FIFOs.....	889
Chapter 45: Introduction to System V IPC.....	921
Chapter 46: System V Message Queues	937

Chapter 47: System V Semaphores	965
Chapter 48: System V Shared Memory	997
Chapter 49: Memory Mappings	1017
Chapter 50: Virtual Memory Operations	1045
Chapter 51: Introduction to POSIX IPC	1057
Chapter 52: POSIX Message Queues	1063
Chapter 53: POSIX Semaphores	1089
Chapter 54: POSIX Shared Memory	1107
Chapter 55: File Locking	1117
Chapter 56: Sockets: Introduction	1149
Chapter 57: Sockets: UNIX Domain	1165
Chapter 58: Sockets: Fundamentals of TCP/IP Networks	1179
Chapter 59: Sockets: Internet Domains	1197
Chapter 60: Sockets: Server Design	1239
Chapter 61: Sockets: Advanced Topics	1253
Chapter 62: Terminals	1289
Chapter 63: Alternative I/O Models	1325
Chapter 64: Pseudoterminals	1375
Appendix A: Tracing System Calls	1401
Appendix B: Parsing Command-Line Options	1405
Appendix C: Casting the NULL Pointer	1413
Appendix D: Kernel Configuration	1417
Appendix E: Further Sources of Information	1419
Appendix F: Solutions to Selected Exercises	1425
Bibliography	1437
Index	1447

CONTENTS IN DETAIL

PREFACE

xxxi

1	HISTORY AND STANDARDS	1
1.1	A Brief History of UNIX and C	2
1.2	A Brief History of Linux	5
1.2.1	The GNU Project	5
1.2.2	The Linux Kernel	6
1.3	Standardization	10
1.3.1	The C Programming Language	10
1.3.2	The First POSIX Standards	11
1.3.3	X/Open Company and The Open Group	13
1.3.4	SUSv3 and POSIX.1-2001	13
1.3.5	SUSv4 and POSIX.1-2008	15
1.3.6	UNIX Standards Timeline	16
1.3.7	Implementation Standards	17
1.3.8	Linux, Standards, and the Linux Standard Base	18
1.4	Summary	19
2	FUNDAMENTAL CONCEPTS	21
2.1	The Core Operating System: The Kernel	21
2.2	The Shell	24
2.3	Users and Groups	26
2.4	Single Directory Hierarchy, Directories, Links, and Files	27
2.5	File I/O Model	29
2.6	Programs	30
2.7	Processes	31
2.8	Memory Mappings	35
2.9	Static and Shared Libraries	35
2.10	Interprocess Communication and Synchronization	36
2.11	Signals	37
2.12	Threads	38
2.13	Process Groups and Shell Job Control	38
2.14	Sessions, Controlling Terminals, and Controlling Processes	39
2.15	Pseudoterminals	39
2.16	Date and Time	40
2.17	Client-Server Architecture	40
2.18	Realtime	41
2.19	The /proc File System	42
2.20	Summary	42
3	SYSTEM PROGRAMMING CONCEPTS	43
3.1	System Calls	43
3.2	Library Functions	46
3.3	The Standard C Library; The GNU C Library (<i>glibc</i>)	47
3.4	Handling Errors from System Calls and Library Functions	48
3.5	Notes on the Example Programs in This Book	50
3.5.1	Command-Line Options and Arguments	50
3.5.2	Common Functions and Header Files	51

3.6	Portability Issues	61
3.6.1	Feature Test Macros	61
3.6.2	System Data Types	63
3.6.3	Miscellaneous Portability Issues	66
3.7	Summary	68
3.8	Exercise	68
4	FILE I/O: THE UNIVERSAL I/O MODEL	69
4.1	Overview	69
4.2	Universality of I/O	72
4.3	Opening a File: <i>open()</i>	72
4.3.1	The <i>open()</i> <i>flags</i> Argument	74
4.3.2	Errors from <i>open()</i>	77
4.3.3	The <i>creat()</i> System Call	78
4.4	Reading from a File: <i>read()</i>	79
4.5	Writing to a File: <i>write()</i>	80
4.6	Closing a File: <i>close()</i>	80
4.7	Changing the File Offset: <i>lseek()</i>	81
4.8	Operations Outside the Universal I/O Model: <i>ioctl()</i>	86
4.9	Summary	86
4.10	Exercises	87
5	FILE I/O: FURTHER DETAILS	89
5.1	Atomicity and Race Conditions	90
5.2	File Control Operations: <i>fcntl()</i>	92
5.3	Open File Status Flags	93
5.4	Relationship Between File Descriptors and Open Files	94
5.5	Duplicating File Descriptors	96
5.6	File I/O at a Specified Offset: <i>pread()</i> and <i>pwrite()</i>	98
5.7	Scatter-Gather I/O: <i>readv()</i> and <i>writev()</i>	99
5.8	Truncating a File: <i>truncate()</i> and <i>ftruncate()</i>	103
5.9	Nonblocking I/O	103
5.10	I/O on Large Files	104
5.11	The <i>/dev/fd</i> Directory	107
5.12	Creating Temporary Files	108
5.13	Summary	109
5.14	Exercises	110
6	PROCESSES	113
6.1	Processes and Programs	113
6.2	Process ID and Parent Process ID	114
6.3	Memory Layout of a Process	115
6.4	Virtual Memory Management	118
6.5	The Stack and Stack Frames	121
6.6	Command-Line Arguments (<i>argc</i> , <i>argv</i>)	122
6.7	Environment List	125
6.8	Performing a Nonlocal Goto: <i>setjmp()</i> and <i>longjmp()</i>	131
6.9	Summary	138
6.10	Exercises	138

7	MEMORY ALLOCATION	139
7.1	Allocating Memory on the Heap	139
7.1.1	Adjusting the Program Break: <i>brk()</i> and <i>sbrk()</i>	139
7.1.2	Allocating Memory on the Heap: <i>malloc()</i> and <i>free()</i>	140
7.1.3	Implementation of <i>malloc()</i> and <i>free()</i>	144
7.1.4	Other Methods of Allocating Memory on the Heap	147
7.2	Allocating Memory on the Stack: <i>alloca()</i>	150
7.3	Summary	151
7.4	Exercises	152
8	USERS AND GROUPS	153
8.1	The Password File: <i>/etc/passwd</i>	153
8.2	The Shadow Password File: <i>/etc/shadow</i>	155
8.3	The Group File: <i>/etc/group</i>	155
8.4	Retrieving User and Group Information	157
8.5	Password Encryption and User Authentication	162
8.6	Summary	166
8.7	Exercises	166
9	PROCESS CREDENTIALS	167
9.1	Real User ID and Real Group ID	167
9.2	Effective User ID and Effective Group ID	168
9.3	Set-User-ID and Set-Group-ID Programs	168
9.4	Saved Set-User-ID and Saved Set-Group-ID	170
9.5	File-System User ID and File-System Group ID	171
9.6	Supplementary Group IDs	172
9.7	Retrieving and Modifying Process Credentials	172
9.7.1	Retrieving and Modifying Real, Effective, and Saved Set IDs	172
9.7.2	Retrieving and Modifying File-System IDs	178
9.7.3	Retrieving and Modifying Supplementary Group IDs	178
9.7.4	Summary of Calls for Modifying Process Credentials	180
9.7.5	Example: Displaying Process Credentials	182
9.8	Summary	183
9.9	Exercises	184
10	TIME	185
10.1	Calendar Time	186
10.2	Time-Conversion Functions	187
10.2.1	Converting <i>time_t</i> to Printable Form	188
10.2.2	Converting Between <i>time_t</i> and Broken-Down Time	189
10.2.3	Converting Between Broken-Down Time and Printable Form	191
10.3	Timezones	197
10.4	Locales	200
10.5	Updating the System Clock	204
10.6	The Software Clock (Jiffies)	205
10.7	Process Time	206
10.8	Summary	209
10.9	Exercise	210

11	SYSTEM LIMITS AND OPTIONS	211
11.1	System Limits.....	212
11.2	Retrieving System Limits (and Options) at Run Time.....	215
11.3	Retrieving File-Related Limits (and Options) at Run Time.....	217
11.4	Indeterminate Limits	219
11.5	System Options.....	219
11.6	Summary.....	221
11.7	Exercises	222
12	SYSTEM AND PROCESS INFORMATION	223
12.1	The /proc File System.....	223
12.1.1	Obtaining Information About a Process: <i>/proc/PID</i>	224
12.1.2	System Information Under /proc.....	226
12.1.3	Accessing /proc Files	226
12.2	System Identification: <i>uname()</i>	229
12.3	Summary.....	231
12.4	Exercises	231
13	FILE I/O BUFFERING	233
13.1	Kernel Buffering of File I/O: The Buffer Cache	233
13.2	Buffering in the <i>stdio</i> Library	237
13.3	Controlling Kernel Buffering of File I/O.....	239
13.4	Summary of I/O Buffering	243
13.5	Advising the Kernel About I/O Patterns.....	244
13.6	Bypassing the Buffer Cache: Direct I/O.....	246
13.7	Mixing Library Functions and System Calls for File I/O	248
13.8	Summary.....	249
13.9	Exercises	250
14	FILE SYSTEMS	251
14.1	Device Special Files (Devices)	252
14.2	Disks and Partitions	253
14.3	File Systems	254
14.4	Inodes	256
14.5	The Virtual File System (VFS)	259
14.6	Journaling File Systems.....	260
14.7	Single Directory Hierarchy and Mount Points	261
14.8	Mounting and Unmounting File Systems	262
14.8.1	Mounting a File System: <i>mount()</i>	264
14.8.2	Unmounting a File System: <i>umount()</i> and <i>umount2()</i>	269
14.9	Advanced Mount Features	271
14.9.1	Mounting a File System at Multiple Mount Points.....	271
14.9.2	Stacking Multiple Mounts on the Same Mount Point.....	271
14.9.3	Mount Flags That Are Per-Mount Options	272
14.9.4	Bind Mounts.....	272
14.9.5	Recursive Bind Mounts.....	273
14.10	A Virtual Memory File System: <i>tmpfs</i>	274
14.11	Obtaining Information About a File System: <i>statvfs()</i>	276
14.12	Summary.....	277
14.13	Exercise	278

15	FILE ATTRIBUTES	279
15.1	Retrieving File Information: <i>stat()</i>	279
15.2	File Timestamps	285
15.2.1	Changing File Timestamps with <i>utime()</i> and <i>utimes()</i>	287
15.2.2	Changing File Timestamps with <i>utimensat()</i> and <i>futimens()</i>	289
15.3	File Ownership	291
15.3.1	Ownership of New Files	291
15.3.2	Changing File Ownership: <i>chown()</i> , <i>fchown()</i> , and <i>lchown()</i>	291
15.4	File Permissions	294
15.4.1	Permissions on Regular Files	294
15.4.2	Permissions on Directories	297
15.4.3	Permission-Checking Algorithm	297
15.4.4	Checking File Accessibility: <i>access()</i>	299
15.4.5	Set-User-ID, Set-Group-ID, and Sticky Bits	300
15.4.6	The Process File Mode Creation Mask: <i>umask()</i>	301
15.4.7	Changing File Permissions: <i>chmod()</i> and <i>fchmod()</i>	303
15.5	I-node Flags (<i>ext2</i> Extended File Attributes)	304
15.6	Summary	308
15.7	Exercises	309
16	EXTENDED ATTRIBUTES	311
16.1	Overview	311
16.2	Extended Attribute Implementation Details	313
16.3	System Calls for Manipulating Extended Attributes	314
16.4	Summary	318
16.5	Exercise	318
17	ACCESS CONTROL LISTS	319
17.1	Overview	320
17.2	ACL Permission-Checking Algorithm	321
17.3	Long and Short Text Forms for ACLs	323
17.4	The <i>ACL_MASK</i> Entry and the ACL Group Class	324
17.5	The <i>getfacl</i> and <i>setfacl</i> Commands	325
17.6	Default ACLs and File Creation	327
17.7	ACL Implementation Limits	328
17.8	The ACL API	329
17.9	Summary	337
17.10	Exercise	337
18	DIRECTORIES AND LINKS	339
18.1	Directories and (Hard) Links	339
18.2	Symbolic (Soft) Links	342
18.3	Creating and Removing (Hard) Links: <i>link()</i> and <i>unlink()</i>	344
18.4	Changing the Name of a File: <i>rename()</i>	348
18.5	Working with Symbolic Links: <i>symlink()</i> and <i>readlink()</i>	349
18.6	Creating and Removing Directories: <i>mkdir()</i> and <i>rmdir()</i>	350
18.7	Removing a File or Directory: <i>remove()</i>	352
18.8	Reading Directories: <i>opendir()</i> and <i>readdir()</i>	352
18.9	File Tree Walking: <i>nftw()</i>	358
18.10	The Current Working Directory of a Process	363
18.11	Operating Relative to a Directory File Descriptor	365
18.12	Changing the Root Directory of a Process: <i>chroot()</i>	367
18.13	Resolving a Pathname: <i>realpath()</i>	369

18.14	Parsing Pathname Strings: <i>dirname()</i> and <i>basename()</i>	370
18.15	Summary.....	372
18.16	Exercises	373

19 MONITORING FILE EVENTS 375

19.1	Overview	376
19.2	The <i>inotify</i> API	376
19.3	<i>inotify</i> Events	378
19.4	Reading <i>inotify</i> Events.....	379
19.5	Queue Limits and <i>/proc</i> Files.....	385
19.6	An Older System for Monitoring File Events: <i>dnotify</i>	386
19.7	Summary.....	386
19.8	Exercise	386

20 SIGNALS: FUNDAMENTAL CONCEPTS 387

20.1	Concepts and Overview	388
20.2	Signal Types and Default Actions	390
20.3	Changing Signal Dispositions: <i>signal()</i>	397
20.4	Introduction to Signal Handlers	398
20.5	Sending Signals: <i>kill()</i>	401
20.6	Checking for the Existence of a Process.....	403
20.7	Other Ways of Sending Signals: <i>raise()</i> and <i>killpg()</i>	404
20.8	Displaying Signal Descriptions.....	406
20.9	Signal Sets	406
20.10	The Signal Mask (Blocking Signal Delivery)	410
20.11	Pending Signals	411
20.12	Signals Are Not Queued.....	412
20.13	Changing Signal Dispositions: <i>sigaction()</i>	416
20.14	Waiting for a Signal: <i>pause()</i>	418
20.15	Summary.....	418
20.16	Exercises	419

21 SIGNALS: SIGNAL HANDLERS 421

21.1	Designing Signal Handlers	422
21.1.1	Signals Are Not Queued (Revisited)	422
21.1.2	Reentrant and Async-Signal-Safe Functions	422
21.1.3	Global Variables and the <i>sig_atomic_t</i> Data Type	428
21.2	Other Methods of Terminating a Signal Handler	428
21.2.1	Performing a Nonlocal Goto from a Signal Handler	429
21.2.2	Terminating a Process Abnormally: <i>abort()</i>	433
21.3	Handling a Signal on an Alternate Stack: <i>sigaltstack()</i>	434
21.4	The <i>SA_SIGINFO</i> Flag.....	437
21.5	Interruption and Restarting of System Calls	442
21.6	Summary.....	445
21.7	Exercise	446

22 SIGNALS: ADVANCED FEATURES 447

22.1	Core Dump Files	448
22.2	Special Cases for Delivery, Disposition, and Handling	450
22.3	Interruptible and Uninterruptible Process Sleep States.....	451
22.4	Hardware-Generated Signals.....	452
22.5	Synchronous and Asynchronous Signal Generation	452

25.5	Summary.....	538
25.6	Exercise	539
26	MONITORING CHILD PROCESSES	541
26.1	Waiting on a Child Process	541
26.1.1	The <i>wait()</i> System Call.....	541
26.1.2	The <i>waitpid()</i> System Call	544
26.1.3	The Wait Status Value	545
26.1.4	Process Termination from a Signal Handler	549
26.1.5	The <i>waitid()</i> System Call.....	550
26.1.6	The <i>wait3()</i> and <i>wait4()</i> System Calls	552
26.2	Orphans and Zombies	553
26.3	The SIGCHLD Signal	555
26.3.1	Establishing a Handler for SIGCHLD	555
26.3.2	Delivery of SIGCHLD for Stopped Children	559
26.3.3	Ignoring Dead Child Processes	559
26.4	Summary.....	561
26.5	Exercises	562
27	PROGRAM EXECUTION	563
27.1	Executing a New Program: <i>execve()</i>	563
27.2	The <i>exec()</i> Library Functions.....	567
27.2.1	The PATH Environment Variable	568
27.2.2	Specifying Program Arguments as a List.....	570
27.2.3	Passing the Caller's Environment to the New Program	570
27.2.4	Executing a File Referred to by a Descriptor: <i>fexecve()</i>	571
27.3	Interpreter Scripts	572
27.4	File Descriptors and <i>exec()</i>	575
27.5	Signals and <i>exec()</i>	578
27.6	Executing a Shell Command: <i>system()</i>	579
27.7	Implementing <i>system()</i>	582
27.8	Summary.....	588
27.9	Exercises	589
28	PROCESS CREATION AND PROGRAM EXECUTION IN MORE DETAIL	591
28.1	Process Accounting.....	591
28.2	The <i>clone()</i> System Call	598
28.2.1	The <i>clone()</i> <i>flags</i> Argument	603
28.2.2	Extensions to <i>waitpid()</i> for Cloned Children	609
28.3	Speed of Process Creation.....	610
28.4	Effect of <i>exec()</i> and <i>fork()</i> on Process Attributes.....	612
28.5	Summary.....	616
28.6	Exercise	616
29	THREADS: INTRODUCTION	617
29.1	Overview	617
29.2	Background Details of the Pthreads API.....	620
29.3	Thread Creation.....	622
29.4	Thread Termination.....	623
29.5	Thread IDs.....	624
29.6	Joining with a Terminated Thread.....	625
29.7	Detaching a Thread.....	627

29.8	Thread Attributes	628
29.9	Threads Versus Processes	629
29.10	Summary	629
29.11	Exercises	630

30 THREADS: THREAD SYNCHRONIZATION 631

30.1	Protecting Accesses to Shared Variables: Mutexes	631
30.1.1	Statically Allocated Mutexes	635
30.1.2	Locking and Unlocking a Mutex	635
30.1.3	Performance of Mutexes	638
30.1.4	Mutex Deadlocks	639
30.1.5	Dynamically Initializing a Mutex	639
30.1.6	Mutex Attributes	640
30.1.7	Mutex Types	640
30.2	Signaling Changes of State: Condition Variables	642
30.2.1	Statically Allocated Condition Variables	643
30.2.2	Signaling and Waiting on Condition Variables	643
30.2.3	Testing a Condition Variable's Predicate	647
30.2.4	Example Program: Joining Any Terminated Thread	648
30.2.5	Dynamically Allocated Condition Variables	651
30.3	Summary	652
30.4	Exercises	652

31 THREADS: THREAD SAFETY AND PER-THREAD STORAGE 655

31.1	Thread Safety (and Reentrancy Revisited)	655
31.2	One-Time Initialization	658
31.3	Thread-Specific Data	659
31.3.1	Thread-Specific Data from the Library Function's Perspective	660
31.3.2	Overview of the Thread-Specific Data API	660
31.3.3	Details of the Thread-Specific Data API	661
31.3.4	Employing the Thread-Specific Data API	663
31.3.5	Thread-Specific Data Implementation Limits	668
31.4	Thread-Local Storage	668
31.5	Summary	669
31.6	Exercises	670

32 THREADS: THREAD CANCELLATION 671

32.1	Canceling a Thread	671
32.2	Cancellation State and Type	672
32.3	Cancellation Points	673
32.4	Testing for Thread Cancellation	675
32.5	Cleanup Handlers	676
32.6	Asynchronous Cancelability	680
32.7	Summary	680

33 THREADS: FURTHER DETAILS 681

33.1	Thread Stacks	681
33.2	Threads and Signals	682
33.2.1	How the UNIX Signal Model Maps to Threads	682
33.2.2	Manipulating the Thread Signal Mask	684
33.2.3	Sending a Signal to a Thread	684
33.2.4	Dealing with Asynchronous Signals Sanely	685

33.3	Threads and Process Control.....	686
33.4	Thread Implementation Models	687
33.5	Linux Implementations of POSIX Threads	689
33.5.1	LinuxThreads	689
33.5.2	NPTL	692
33.5.3	Which Threading Implementation?.....	694
33.6	Advanced Features of the Pthreads API	696
33.7	Summary.....	696
33.8	Exercises	697

34 PROCESS GROUPS, SESSIONS, AND JOB CONTROL 699

34.1	Overview	699
34.2	Process Groups	701
34.3	Sessions	704
34.4	Controlling Terminals and Controlling Processes.....	706
34.5	Foreground and Background Process Groups	708
34.6	The SIGHUP Signal.....	709
34.6.1	Handling of SIGHUP by the Shell	710
34.6.2	SIGHUP and Termination of the Controlling Process.....	712
34.7	Job Control.....	714
34.7.1	Using Job Control Within the Shell	714
34.7.2	Implementing Job Control.....	717
34.7.3	Handling Job-Control Signals	722
34.7.4	Orphaned Process Groups (and SIGHUP Revisited)	725
34.8	Summary.....	730
34.9	Exercises	731

35 PROCESS PRIORITIES AND SCHEDULING 733

35.1	Process Priorities (Nice Values)	733
35.2	Overview of Realtime Process Scheduling.....	737
35.2.1	The SCHED_RR Policy	739
35.2.2	The SCHED_FIFO Policy	740
35.2.3	The SCHED_BATCH and SCHED_IDLE Policies.....	740
35.3	Realtime Process Scheduling API	740
35.3.1	Realtime Priority Ranges	740
35.3.2	Modifying and Retrieving Policies and Priorities.....	741
35.3.3	Relinquishing the CPU	747
35.3.4	The SCHED_RR Time Slice	747
35.4	CPU Affinity.....	748
35.5	Summary.....	751
35.6	Exercises	751

36 PROCESS RESOURCES 753

36.1	Process Resource Usage	753
36.2	Process Resource Limits	755
36.3	Details of Specific Resource Limits	760
36.4	Summary.....	765
36.5	Exercises	765

37 DAEMONS 767

37.1	Overview	767
37.2	Creating a Daemon	768

37.3	Guidelines for Writing Daemons	771
37.4	Using SIGHUP to Reinitialize a Daemon	772
37.5	Logging Messages and Errors Using <i>syslog</i>	775
37.5.1	Overview	775
37.5.2	The <i>syslog</i> API	777
37.5.3	The <i>/etc/syslog.conf</i> File	781
37.6	Summary	782
37.7	Exercise	782

38 WRITING SECURE PRIVILEGED PROGRAMS 783

38.1	Is a Set-User-ID or Set-Group-ID Program Required?	784
38.2	Operate with Least Privilege	784
38.3	Be Careful When Executing a Program	787
38.4	Avoid Exposing Sensitive Information	788
38.5	Confine the Process	789
38.6	Beware of Signals and Race Conditions	790
38.7	Pitfalls When Performing File Operations and File I/O	790
38.8	Don't Trust Inputs or the Environment	791
38.9	Beware of Buffer Overruns	792
38.10	Beware of Denial-of-Service Attacks	793
38.11	Check Return Statuses and Fail Safely	794
38.12	Summary	795
38.13	Exercises	796

39 CAPABILITIES 797

39.1	Rationale for Capabilities	797
39.2	The Linux Capabilities	798
39.3	Process and File Capabilities	798
39.3.1	Process Capabilities	798
39.3.2	File Capabilities	799
39.3.3	Purpose of the Process Permitted and Effective Capability Sets	802
39.3.4	Purpose of the File Permitted and Effective Capability Sets	802
39.3.5	Purpose of the Process and File Inheritable Sets	802
39.3.6	Assigning and Viewing File Capabilities from the Shell	803
39.4	The Modern Capabilities Implementation	804
39.5	Transformation of Process Capabilities During <i>exec()</i>	805
39.5.1	Capability Bounding Set	805
39.5.2	Preserving <i>root</i> Semantics	806
39.6	Effect on Process Capabilities of Changing User IDs	806
39.7	Changing Process Capabilities Programmatically	807
39.8	Creating Capabilities-Only Environments	811
39.9	Discovering the Capabilities Required by a Program	813
39.10	Older Kernels and Systems Without File Capabilities	814
39.11	Summary	816
39.12	Exercise	816

40 LOGIN ACCOUNTING 817

40.1	Overview of the <i>utmp</i> and <i>wtmp</i> Files	817
40.2	The <i>utmpx</i> API	818
40.3	The <i>utmpx</i> Structure	818
40.4	Retrieving Information from the <i>utmp</i> and <i>wtmp</i> Files	821
40.5	Retrieving the Login Name: <i>getlogin()</i>	825
40.6	Updating the <i>utmp</i> and <i>wtmp</i> Files for a Login Session	825

40.7	The lastlog File	830
40.8	Summary.....	832
40.9	Exercises	832

41 FUNDAMENTALS OF SHARED LIBRARIES 833

41.1	Object Libraries	833
41.2	Static Libraries	834
41.3	Overview of Shared Libraries.....	836
41.4	Creating and Using Shared Libraries—A First Pass	837
41.4.1	Creating a Shared Library.....	837
41.4.2	Position-Independent Code.....	838
41.4.3	Using a Shared Library.....	839
41.4.4	The Shared Library Soname	840
41.5	Useful Tools for Working with Shared Libraries	843
41.6	Shared Library Versions and Naming Conventions	844
41.7	Installing Shared Libraries	847
41.8	Compatible Versus Incompatible Libraries.....	850
41.9	Upgrading Shared Libraries.....	850
41.10	Specifying Library Search Directories in an Object File	851
41.11	Finding Shared Libraries at Run Time	854
41.12	Run-Time Symbol Resolution	854
41.13	Using a Static Library Instead of a Shared Library	856
41.14	Summary.....	856
41.15	Exercise	857

42 ADVANCED FEATURES OF SHARED LIBRARIES 859

42.1	Dynamically Loaded Libraries	859
42.1.1	Opening a Shared Library: <i>dlopen()</i>	860
42.1.2	Diagnosing Errors: <i>dlderror()</i>	862
42.1.3	Obtaining the Address of a Symbol: <i>dlsym()</i>	862
42.1.4	Closing a Shared Library: <i>dlclose()</i>	866
42.1.5	Obtaining Information About Loaded Symbols: <i>dladdr()</i>	866
42.1.6	Accessing Symbols in the Main Program.....	867
42.2	Controlling Symbol Visibility	867
42.3	Linker Version Scripts.....	868
42.3.1	Controlling Symbol Visibility with Version Scripts	868
42.3.2	Symbol Versioning	870
42.4	Initialization and Finalization Functions.....	872
42.5	Preloading Shared Libraries.....	873
42.6	Monitoring the Dynamic Linker: LD_DEBUG.....	874
42.7	Summary.....	875
42.8	Exercises	876

43 INTERPROCESS COMMUNICATION OVERVIEW 877

43.1	A Taxonomy of IPC Facilities	877
43.2	Communication Facilities.....	879
43.3	Synchronization Facilities	880
43.4	Comparing IPC Facilities	882
43.5	Summary.....	887
43.6	Exercises	887

44	PIPES AND FIFOs	889
44.1	Overview	889
44.2	Creating and Using Pipes	892
44.3	Pipes as a Method of Process Synchronization	897
44.4	Using Pipes to Connect Filters	899
44.5	Talking to a Shell Command via a Pipe: <i>popen()</i>	902
44.6	Pipes and <i>stdio</i> Buffering	906
44.7	FIFOs	906
44.8	A Client-Server Application Using FIFOs	909
44.9	Nonblocking I/O	915
44.10	Semantics of <i>read()</i> and <i>write()</i> on Pipes and FIFOs	917
44.11	Summary	918
44.12	Exercises	919
45	INTRODUCTION TO SYSTEM V IPC	921
45.1	API Overview	922
45.2	IPC Keys	925
45.3	Associated Data Structure and Object Permissions	927
45.4	IPC Identifiers and Client-Server Applications	929
45.5	Algorithm Employed by System V IPC <i>get</i> Calls	931
45.6	The <i>ipcs</i> and <i>ipcrm</i> Commands	934
45.7	Obtaining a List of All IPC Objects	935
45.8	IPC Limits	935
45.9	Summary	936
45.10	Exercises	936
46	SYSTEM V MESSAGE QUEUES	937
46.1	Creating or Opening a Message Queue	938
46.2	Exchanging Messages	940
46.2.1	Sending Messages	940
46.2.2	Receiving Messages	943
46.3	Message Queue Control Operations	947
46.4	Message Queue Associated Data Structure	948
46.5	Message Queue Limits	950
46.6	Displaying All Message Queues on the System	951
46.7	Client-Server Programming with Message Queues	953
46.8	A File-Server Application Using Message Queues	955
46.9	Disadvantages of System V Message Queues	961
46.10	Summary	962
46.11	Exercises	963
47	SYSTEM V SEMAPHORES	965
47.1	Overview	966
47.2	Creating or Opening a Semaphore Set	969
47.3	Semaphore Control Operations	969
47.4	Semaphore Associated Data Structure	972
47.5	Semaphore Initialization	975
47.6	Semaphore Operations	978
47.7	Handling of Multiple Blocked Semaphore Operations	986
47.8	Semaphore Undo Values	986
47.9	Implementing a Binary Semaphores Protocol	988

47.10	Semaphore Limits	991
47.11	Disadvantages of System V Semaphores	993
47.12	Summary.....	993
47.13	Exercises	994

48 SYSTEM V SHARED MEMORY 997

48.1	Overview	998
48.2	Creating or Opening a Shared Memory Segment	998
48.3	Using Shared Memory	999
48.4	Example: Transferring Data via Shared Memory	1001
48.5	Location of Shared Memory in Virtual Memory.....	1006
48.6	Storing Pointers in Shared Memory.....	1010
48.7	Shared Memory Control Operations	1011
48.8	Shared Memory Associated Data Structure.....	1012
48.9	Shared Memory Limits.....	1014
48.10	Summary.....	1015
48.11	Exercises	1016

49 MEMORY MAPPINGS 1017

49.1	Overview	1017
49.2	Creating a Mapping: <i>mmap()</i>	1020
49.3	Unmapping a Mapped Region: <i>munmap()</i>	1023
49.4	File Mappings.....	1024
49.4.1	Private File Mappings.....	1024
49.4.2	Shared File Mappings	1025
49.4.3	Boundary Cases	1029
49.4.4	Memory Protection and File Access Mode Interactions.....	1030
49.5	Synchronizing a Mapped Region: <i>msync()</i>	1031
49.6	Additional <i>mmap()</i> Flags.....	1033
49.7	Anonymous Mappings	1034
49.8	Remapping a Mapped Region: <i>mremap()</i>	1037
49.9	MAP_NORESERVE and Swap Space Overcommitting	1038
49.10	The MAP_FIXED Flag	1040
49.11	Nonlinear Mappings: <i>remap_file_pages()</i>	1041
49.12	Summary.....	1043
49.13	Exercises	1044

50 VIRTUAL MEMORY OPERATIONS 1045

50.1	Changing Memory Protection: <i>mprotect()</i>	1045
50.2	Memory Locking: <i>mlock()</i> and <i>mlockall()</i>	1047
50.3	Determining Memory Residence: <i>mincore()</i>	1051
50.4	Advising Future Memory Usage Patterns: <i>madvise()</i>	1054
50.5	Summary.....	1056
50.6	Exercises	1056

51 INTRODUCTION TO POSIX IPC 1057

51.1	API Overview	1058
51.2	Comparison of System V IPC and POSIX IPC	1061
51.3	Summary.....	1062

52	POSIX MESSAGE QUEUES	1063
52.1	Overview	1064
52.2	Opening, Closing, and Unlinking a Message Queue	1064
52.3	Relationship Between Descriptors and Message Queues	1067
52.4	Message Queue Attributes	1068
52.5	Exchanging Messages	1073
52.5.1	Sending Messages	1073
52.5.2	Receiving Messages	1074
52.5.3	Sending and Receiving Messages with a Timeout	1077
52.6	Message Notification	1077
52.6.1	Receiving Notification via a Signal	1079
52.6.2	Receiving Notification via a Thread	1082
52.7	Linux-Specific Features	1083
52.8	Message Queue Limits	1085
52.9	Comparison of POSIX and System V Message Queues	1086
52.10	Summary	1087
52.11	Exercises	1087
53	POSIX SEMAPHORES	1089
53.1	Overview	1089
53.2	Named Semaphores	1090
53.2.1	Opening a Named Semaphore	1090
53.2.2	Closing a Semaphore	1093
53.2.3	Removing a Named Semaphore	1093
53.3	Semaphore Operations	1094
53.3.1	Waiting on a Semaphore	1094
53.3.2	Posting a Semaphore	1096
53.3.3	Retrieving the Current Value of a Semaphore	1097
53.4	Unnamed Semaphores	1099
53.4.1	Initializing an Unnamed Semaphore	1100
53.4.2	Destroying an Unnamed Semaphore	1102
53.5	Comparisons with Other Synchronization Techniques	1103
53.6	Semaphore Limits	1104
53.7	Summary	1105
53.8	Exercises	1105
54	POSIX SHARED MEMORY	1107
54.1	Overview	1108
54.2	Creating Shared Memory Objects	1109
54.3	Using Shared Memory Objects	1112
54.4	Removing Shared Memory Objects	1114
54.5	Comparisons Between Shared Memory APIs	1115
54.6	Summary	1116
54.7	Exercise	1116
55	FILE LOCKING	1117
55.1	Overview	1117
55.2	File Locking with <i>flock()</i>	1119
55.2.1	Semantics of Lock Inheritance and Release	1122
55.2.2	Limitations of <i>flock()</i>	1123

55.3	Record Locking with <i>fcntl()</i>	1124
55.3.1	Deadlock	1128
55.3.2	Example: An Interactive Locking Program.....	1129
55.3.3	Example: A Library of Locking Functions	1133
55.3.4	Lock Limits and Performance.....	1135
55.3.5	Semantics of Lock Inheritance and Release	1136
55.3.6	Lock Starvation and Priority of Queued Lock Requests.....	1137
55.4	Mandatory Locking.....	1137
55.5	The <i>/proc/locks</i> File	1140
55.6	Running Just One Instance of a Program.....	1142
55.7	Older Locking Techniques	1144
55.8	Summary.....	1146
55.9	Exercises	1147

56 SOCKETS: INTRODUCTION 1149

56.1	Overview	1150
56.2	Creating a Socket: <i>socket()</i>	1153
56.3	Binding a Socket to an Address: <i>bind()</i>	1153
56.4	Generic Socket Address Structures: <i>struct sockaddr</i>	1154
56.5	Stream Sockets.....	1155
56.5.1	Listening for Incoming Connections: <i>listen()</i>	1156
56.5.2	Accepting a Connection: <i>accept()</i>	1157
56.5.3	Connecting to a Peer Socket: <i>connect()</i>	1158
56.5.4	I/O on Stream Sockets	1159
56.5.5	Connection Termination: <i>close()</i>	1159
56.6	Datagram Sockets	1159
56.6.1	Exchanging Datagrams: <i>recvfrom()</i> and <i>sendto()</i>	1160
56.6.2	Using <i>connect()</i> with Datagram Sockets	1162
56.7	Summary.....	1162

57 SOCKETS: UNIX DOMAIN 1165

57.1	UNIX Domain Socket Addresses: <i>struct sockaddr_un</i>	1165
57.2	Stream Sockets in the UNIX Domain	1167
57.3	Datagram Sockets in the UNIX Domain	1171
57.4	UNIX Domain Socket Permissions	1174
57.5	Creating a Connected Socket Pair: <i>socketpair()</i>	1174
57.6	The Linux Abstract Socket Namespace	1175
57.7	Summary.....	1176
57.8	Exercises	1177

58 SOCKETS: FUNDAMENTALS OF TCP/IP NETWORKS 1179

58.1	Internets	1179
58.2	Networking Protocols and Layers	1180
58.3	The Data-Link Layer.....	1182
58.4	The Network Layer: IP	1184
58.5	IP Addresses	1186
58.6	The Transport Layer	1188
58.6.1	Port Numbers	1188
58.6.2	User Datagram Protocol (UDP)	1189
58.6.3	Transmission Control Protocol (TCP).....	1190
58.7	Requests for Comments (RFCs)	1193
58.8	Summary.....	1195

59	SOCKETS: INTERNET DOMAINS	1197
59.1	Internet Domain Sockets	1197
59.2	Network Byte Order	1198
59.3	Data Representation	1199
59.4	Internet Socket Addresses	1202
59.5	Overview of Host and Service Conversion Functions	1204
59.6	The <i>inet_pton()</i> and <i>inet_ntop()</i> Functions	1206
59.7	Client-Server Example (Datagram Sockets)	1207
59.8	Domain Name System (DNS)	1209
59.9	The <i>/etc/services</i> File	1212
59.10	Protocol-Independent Host and Service Conversion	1213
59.10.1	The <i>getaddrinfo()</i> Function	1213
59.10.2	Freeing <i>addrinfo</i> Lists: <i>freeaddrinfo()</i>	1217
59.10.3	Diagnosing Errors: <i>gai_strerror()</i>	1217
59.10.4	The <i>getnameinfo()</i> Function	1218
59.11	Client-Server Example (Stream Sockets)	1219
59.12	An Internet Domain Sockets Library	1225
59.13	Obsolete APIs for Host and Service Conversions	1230
59.13.1	The <i>inet_aton()</i> and <i>inet_ntoa()</i> Functions	1230
59.13.2	The <i>gethostbyname()</i> and <i>gethostbyaddr()</i> Functions	1231
59.13.3	The <i>getservbyname()</i> and <i>getservbyport()</i> Functions	1234
59.14	UNIX Versus Internet Domain Sockets	1235
59.15	Further Information	1235
59.16	Summary	1236
59.17	Exercises	1236
60	SOCKETS: SERVER DESIGN	1239
60.1	Iterative and Concurrent Servers	1239
60.2	An Iterative UDP <i>echo</i> Server	1240
60.3	A Concurrent TCP <i>echo</i> Server	1243
60.4	Other Concurrent Server Designs	1245
60.5	The <i>inetd</i> (Internet Superserver) Daemon	1247
60.6	Summary	1252
60.7	Exercises	1252
61	SOCKETS: ADVANCED TOPICS	1253
61.1	Partial Reads and Writes on Stream Sockets	1254
61.2	The <i>shutdown()</i> System Call	1256
61.3	Socket-Specific I/O System Calls: <i>recv()</i> and <i>send()</i>	1259
61.4	The <i>sendfile()</i> System Call	1260
61.5	Retrieving Socket Addresses	1263
61.6	A Closer Look at TCP	1266
61.6.1	Format of a TCP Segment	1266
61.6.2	TCP Sequence Numbers and Acknowledgements	1268
61.6.3	TCP State Machine and State Transition Diagram	1269
61.6.4	TCP Connection Establishment	1270
61.6.5	TCP Connection Termination	1272
61.6.6	Calling <i>shutdown()</i> on a TCP Socket	1273
61.6.7	The TIME_WAIT State	1274
61.7	Monitoring Sockets: <i>netstat</i>	1275
61.8	Using <i>tcpdump</i> to Monitor TCP Traffic	1276
61.9	Socket Options	1278
61.10	The SO_REUSEADDR Socket Option	1279
61.11	Inheritance of Flags and Options Across <i>accept()</i>	1281

61.12	TCP Versus UDP	1282
61.13	Advanced Features	1283
61.13.1	Out-of-Band Data	1283
61.13.2	The <i>sendmsg()</i> and <i>recvmsg()</i> System Calls	1284
61.13.3	Passing File Descriptors	1284
61.13.4	Receiving Sender Credentials	1284
61.13.5	Sequenced-Packet Sockets	1285
61.13.6	SCTP and DCCP Transport-Layer Protocols	1285
61.14	Summary	1286
61.15	Exercises	1287

62 TERMINALS 1289

62.1	Overview	1290
62.2	Retrieving and Modifying Terminal Attributes	1291
62.3	The <i>stty</i> Command	1294
62.4	Terminal Special Characters	1296
62.5	Terminal Flags	1301
62.6	Terminal I/O Modes	1307
62.6.1	Canonical Mode	1307
62.6.2	Noncanonical Mode	1307
62.6.3	Cooked, Cbreak, and Raw Modes	1309
62.7	Terminal Line Speed (Bit Rate)	1316
62.8	Terminal Line Control	1317
62.9	Terminal Window Size	1319
62.10	Terminal Identification	1321
62.11	Summary	1322
62.12	Exercises	1323

63 ALTERNATIVE I/O MODELS 1325

63.1	Overview	1325
63.1.1	Level-Triggered and Edge-Triggered Notification	1329
63.1.2	Employing Nonblocking I/O with Alternative I/O Models	1330
63.2	I/O Multiplexing	1330
63.2.1	The <i>select()</i> System Call	1331
63.2.2	The <i>poll()</i> System Call	1337
63.2.3	When Is a File Descriptor Ready?	1341
63.2.4	Comparison of <i>select()</i> and <i>poll()</i>	1344
63.2.5	Problems with <i>select()</i> and <i>poll()</i>	1346
63.3	Signal-Driven I/O	1346
63.3.1	When Is “I/O Possible” Signaled?	1351
63.3.2	Refining the Use of Signal-Driven I/O	1352
63.4	The <i>epoll</i> API	1355
63.4.1	Creating an <i>epoll</i> Instance: <i>epoll_create()</i>	1356
63.4.2	Modifying the <i>epoll</i> Interest List: <i>epoll_ctl()</i>	1356
63.4.3	Waiting for Events: <i>epoll_wait()</i>	1358
63.4.4	A Closer Look at <i>epoll</i> Semantics	1363
63.4.5	Performance of <i>epoll</i> Versus I/O Multiplexing	1365
63.4.6	Edge-Triggered Notification	1366
63.5	Waiting on Signals and File Descriptors	1368
63.5.1	The <i>pselect()</i> System Call	1369
63.5.2	The Self-Pipe Trick	1370
63.6	Summary	1373
63.7	Exercises	1374

64	PSEUDOTERMINALS	1375
64.1	Overview	1375
64.2	UNIX 98 Pseudoterminals.....	1380
64.2.1	Opening an Unused Master: <i>posix_openpt()</i>	1380
64.2.2	Changing Slave Ownership and Permissions: <i>grantpt()</i>	1381
64.2.3	Unlocking the Slave: <i>unlockpt()</i>	1382
64.2.4	Obtaining the Name of the Slave: <i>ptsname()</i>	1382
64.3	Opening a Master: <i>ptyMasterOpen()</i>	1383
64.4	Connecting Processes with a Pseudoterminal: <i>ptyFork()</i>	1385
64.5	Pseudoterminal I/O	1388
64.6	Implementing <i>script(1)</i>	1390
64.7	Terminal Attributes and Window Size	1394
64.8	BSD Pseudoterminals	1395
64.9	Summary.....	1397
64.10	Exercises	1398
A	TRACING SYSTEM CALLS	1401
B	PARSING COMMAND-LINE OPTIONS	1405
C	CASTING THE NULL POINTER	1413
D	KERNEL CONFIGURATION	1417
E	FURTHER SOURCES OF INFORMATION	1419
F	SOLUTIONS TO SELECTED EXERCISES	1425
	BIBLIOGRAPHY	1437
	INDEX	1447