
Contents

To Everyone	iii
To Educators	v
To Students	vi
Acknowledgments	vii
Final Words	ix
References	x
1 A Dialogue on the Book	1
2 Introduction to Operating Systems	3
2.1 Virtualizing the CPU	5
2.2 Virtualizing Memory	7
2.3 Concurrency	8
2.4 Persistence	11
2.5 Design Goals	13
2.6 Some History	14
2.7 Summary	18
References	19
I Virtualization	21
3 A Dialogue on Virtualization	23
4 The Abstraction: The Process	25
4.1 The Abstraction: A Process	26
4.2 Process API	27
4.3 Process Creation: A Little More Detail	28
4.4 Process States	29
4.5 Data Structures	31
4.6 Summary	33
References	34
Homework	35

5 Interlude: Process API	37
5.1 The <code>fork()</code> System Call	37
5.2 The <code>wait()</code> System Call	39
5.3 Finally, The <code>exec()</code> System Call	40
5.4 Why? Motivating The API	41
5.5 Other Parts Of The API	44
5.6 Summary	44
References	45
Homework (Code)	46
6 Mechanism: Limited Direct Execution	49
6.1 Basic Technique: Limited Direct Execution	49
6.2 Problem #1: Restricted Operations	50
6.3 Problem #2: Switching Between Processes	54
6.4 Worried About Concurrency?	58
6.5 Summary	59
References	61
Homework (Measurement)	62
7 Scheduling: Introduction	63
7.1 Workload Assumptions	63
7.2 Scheduling Metrics	64
7.3 First In, First Out (FIFO)	64
7.4 Shortest Job First (SJF)	66
7.5 Shortest Time-to-Completion First (STCF)	67
7.6 A New Metric: Response Time	68
7.7 Round Robin	69
7.8 Incorporating I/O	71
7.9 No More Oracle	72
7.10 Summary	72
References	73
Homework	74
8 Scheduling:	
The Multi-Level Feedback Queue	75
8.1 MLFQ: Basic Rules	76
8.2 Attempt #1: How To Change Priority	77
8.3 Attempt #2: The Priority Boost	80
8.4 Attempt #3: Better Accounting	81
8.5 Tuning MLFQ And Other Issues	82
8.6 MLFQ: Summary	83
References	85
Homework	86
9 Scheduling: Proportional Share	87
9.1 Basic Concept: Tickets Represent Your Share	87
9.2 Ticket Mechanisms	89

9.3	Implementation	90
9.4	An Example	91
9.5	How To Assign Tickets?	92
9.6	Why Not Deterministic?	92
9.7	Summary	93
	References	95
	Homework	96
10	Multiprocessor Scheduling (Advanced)	97
10.1	Background: Multiprocessor Architecture	98
10.2	Don't Forget Synchronization	100
10.3	One Final Issue: Cache Affinity	101
10.4	Single-Queue Scheduling	101
10.5	Multi-Queue Scheduling	103
10.6	Linux Multiprocessor Schedulers	106
10.7	Summary	106
	References	107
11	Summary Dialogue on CPU Virtualization	109
12	A Dialogue on Memory Virtualization	111
13	The Abstraction: Address Spaces	113
13.1	Early Systems	113
13.2	Multiprogramming and Time Sharing	114
13.3	The Address Space	115
13.4	Goals	117
13.5	Summary	119
	References	120
14	Interlude: Memory API	123
14.1	Types of Memory	123
14.2	The <code>malloc()</code> Call	124
14.3	The <code>free()</code> Call	126
14.4	Common Errors	126
14.5	Underlying OS Support	129
14.6	Other Calls	130
14.7	Summary	130
	References	131
	Homework (Code)	132
15	Mechanism: Address Translation	135
15.1	Assumptions	136
15.2	An Example	136
15.3	Dynamic (Hardware-based) Relocation	139
15.4	Hardware Support: A Summary	142
15.5	Operating System Issues	143

15.6	Summary	146
References		147
Homework		148
16 Segmentation		149
16.1	Segmentation: Generalized Base/Bounds	149
16.2	Which Segment Are We Referring To?	152
16.3	What About The Stack?	153
16.4	Support for Sharing	154
16.5	Fine-grained vs. Coarse-grained Segmentation	155
16.6	OS Support	155
16.7	Summary	157
References		158
Homework		160
17 Free-Space Management		161
17.1	Assumptions	162
17.2	Low-level Mechanisms	163
17.3	Basic Strategies	171
17.4	Other Approaches	173
17.5	Summary	175
References		176
Homework		177
18 Paging: Introduction		179
18.1	A Simple Example And Overview	179
18.2	Where Are Page Tables Stored?	183
18.3	What's Actually In The Page Table?	184
18.4	Paging: Also Too Slow	185
18.5	A Memory Trace	186
18.6	Summary	189
References		190
Homework		191
19 Paging: Faster Translations (TLBs)		193
19.1	TLB Basic Algorithm	193
19.2	Example: Accessing An Array	195
19.3	Who Handles The TLB Miss?	197
19.4	TLB Contents: What's In There?	199
19.5	TLB Issue: Context Switches	200
19.6	Issue: Replacement Policy	202
19.7	A Real TLB Entry	203
19.8	Summary	204
References		205
Homework (Measurement)		207
20 Paging: Smaller Tables		211

20.1	Simple Solution: Bigger Pages	211
20.2	Hybrid Approach: Paging and Segments	212
20.3	Multi-level Page Tables	215
20.4	Inverted Page Tables	222
20.5	Swapping the Page Tables to Disk	223
20.6	Summary	223
	References	224
	Homework	225
21	Beyond Physical Memory: Mechanisms	227
21.1	Swap Space	228
21.2	The Present Bit	229
21.3	The Page Fault	230
21.4	What If Memory Is Full?	231
21.5	Page Fault Control Flow	232
21.6	When Replacements Really Occur	233
21.7	Summary	234
	References	235
22	Beyond Physical Memory: Policies	237
22.1	Cache Management	237
22.2	The Optimal Replacement Policy	238
22.3	A Simple Policy: FIFO	240
22.4	Another Simple Policy: Random	242
22.5	Using History: LRU	243
22.6	Workload Examples	244
22.7	Implementing Historical Algorithms	247
22.8	Approximating LRU	248
22.9	Considering Dirty Pages	249
22.10	Other VM Policies	250
22.11	Thrashing	250
22.12	Summary	251
	References	252
	Homework	254
23	The VAX/VMS Virtual Memory System	255
23.1	Background	255
23.2	Memory Management Hardware	256
23.3	A Real Address Space	257
23.4	Page Replacement	259
23.5	Other Neat VM Tricks	260
23.6	Summary	262
	References	263
24	Summary Dialogue on Memory Virtualization	265

II Concurrency	269
25 A Dialogue on Concurrency	271
26 Concurrency: An Introduction	273
26.1 An Example: Thread Creation	274
26.2 Why It Gets Worse: Shared Data	277
26.3 The Heart Of The Problem: Uncontrolled Scheduling	279
26.4 The Wish For Atomicity	281
26.5 One More Problem: Waiting For Another	283
26.6 Summary: Why in OS Class?	283
References	285
Homework	286
27 Interlude: Thread API	289
27.1 Thread Creation	289
27.2 Thread Completion	290
27.3 Locks	293
27.4 Condition Variables	295
27.5 Compiling and Running	297
27.6 Summary	297
References	299
28 Locks	301
28.1 Locks: The Basic Idea	301
28.2 Pthread Locks	302
28.3 Building A Lock	303
28.4 Evaluating Locks	303
28.5 Controlling Interrupts	304
28.6 Test And Set (Atomic Exchange)	306
28.7 Building A Working Spin Lock	307
28.8 Evaluating Spin Locks	309
28.9 Compare-And-Swap	309
28.10 Load-Linked and Store-Conditional	311
28.11 Fetch-And-Add	312
28.12 Too Much Spinning: What Now?	313
28.13 A Simple Approach: Just Yield, Baby	314
28.14 Using Queues: Sleeping Instead Of Spinning	315
28.15 Different OS, Different Support	317
28.16 Two-Phase Locks	318
28.17 Summary	319
References	320
Homework	322
29 Lock-based Concurrent Data Structures	325
29.1 Concurrent Counters	325
29.2 Concurrent Linked Lists	330

29.3 Concurrent Queues	333
29.4 Concurrent Hash Table	334
29.5 Summary	336
References	337
30 Condition Variables	339
30.1 Definition and Routines	340
30.2 The Producer/Consumer (Bounded Buffer) Problem	343
30.3 Covering Conditions	351
30.4 Summary	352
References	353
31 Semaphores	355
31.1 Semaphores: A Definition	355
31.2 Binary Semaphores (Locks)	357
31.3 Semaphores As Condition Variables	358
31.4 The Producer/Consumer (Bounded Buffer) Problem	360
31.5 Reader-Writer Locks	364
31.6 The Dining Philosophers	366
31.7 How To Implement Semaphores	369
31.8 Summary	370
References	371
32 Common Concurrency Problems	373
32.1 What Types Of Bugs Exist?	373
32.2 Non-Deadlock Bugs	374
32.3 Deadlock Bugs	377
32.4 Summary	385
References	386
33 Event-based Concurrency (Advanced)	389
33.1 The Basic Idea: An Event Loop	389
33.2 An Important API: <code>select()</code> (or <code>poll()</code>)	390
33.3 Using <code>select()</code>	391
33.4 Why Simpler? No Locks Needed	392
33.5 A Problem: Blocking System Calls	393
33.6 A Solution: Asynchronous I/O	393
33.7 Another Problem: State Management	396
33.8 What Is Still Difficult With Events	397
33.9 Summary	397
References	398
34 Summary Dialogue on Concurrency	399

III Persistence	401
35 A Dialogue on Persistence	403
36 I/O Devices	405
36.1 System Architecture	405
36.2 A Canonical Device	406
36.3 The Canonical Protocol	407
36.4 Lowering CPU Overhead With Interrupts	408
36.5 More Efficient Data Movement With DMA	409
36.6 Methods Of Device Interaction	410
36.7 Fitting Into The OS: The Device Driver	411
36.8 Case Study: A Simple IDE Disk Driver	412
36.9 Historical Notes	415
36.10 Summary	415
References	416
37 Hard Disk Drives	419
37.1 The Interface	419
37.2 Basic Geometry	420
37.3 A Simple Disk Drive	421
37.4 I/O Time: Doing The Math	424
37.5 Disk Scheduling	428
37.6 Summary	432
References	433
Homework	434
38 Redundant Arrays of Inexpensive Disks (RAIDs)	437
38.1 Interface And RAID Internals	438
38.2 Fault Model	439
38.3 How To Evaluate A RAID	439
38.4 RAID Level 0: Striping	440
38.5 RAID Level 1: Mirroring	443
38.6 RAID Level 4: Saving Space With Parity	446
38.7 RAID Level 5: Rotating Parity	450
38.8 RAID Comparison: A Summary	451
38.9 Other Interesting RAID Issues	452
38.10 Summary	452
References	453
Homework	455
39 Interlude: File and Directories	457
39.1 Files and Directories	457
39.2 The File System Interface	459
39.3 Creating Files	459
39.4 Reading and Writing Files	460
39.5 Reading And Writing, But Not Sequentially	462

39.6	Writing Immediately with <code>fsync()</code>	463
39.7	Renaming Files	464
39.8	Getting Information About Files	465
39.9	Removing Files	466
39.10	Making Directories	466
39.11	Reading Directories	467
39.12	Deleting Directories	468
39.13	Hard Links	468
39.14	Symbolic Links	470
39.15	Making and Mounting a File System	472
39.16	Summary	473
	References	474
	Homework	475
40	File System Implementation	477
40.1	The Way To Think	477
40.2	Overall Organization	478
40.3	File Organization: The Inode	480
40.4	Directory Organization	485
40.5	Free Space Management	485
40.6	Access Paths: Reading and Writing	486
40.7	Caching and Buffering	490
40.8	Summary	492
	References	493
	Homework	494
41	Locality and The Fast File System	495
41.1	The Problem: Poor Performance	495
41.2	FFS: Disk Awareness Is The Solution	497
41.3	Organizing Structure: The Cylinder Group	497
41.4	Policies: How To Allocate Files and Directories	498
41.5	Measuring File Locality	499
41.6	The Large-File Exception	500
41.7	A Few Other Things About FFS	502
41.8	Summary	504
	References	505
42	Crash Consistency: FSCK and Journaling	507
42.1	A Detailed Example	508
42.2	Solution #1: The File System Checker	511
42.3	Solution #2: Journaling (or Write-Ahead Logging)	513
42.4	Solution #3: Other Approaches	523
42.5	Summary	524
	References	525
43	Log-structured File Systems	527
43.1	Writing To Disk Sequentially	528

43.2	Writing Sequentially And Effectively	529
43.3	How Much To Buffer?	530
43.4	Problem: Finding Inodes	531
43.5	Solution Through Indirection: The Inode Map	531
43.6	The Checkpoint Region	532
43.7	Reading A File From Disk: A Recap	533
43.8	What About Directories?	533
43.9	A New Problem: Garbage Collection	534
43.10	Determining Block Liveness	536
43.11	A Policy Question: Which Blocks To Clean, And When?	537
43.12	Crash Recovery And The Log	537
43.13	Summary	538
	References	540
44	Data Integrity and Protection	543
44.1	Disk Failure Modes	543
44.2	Handling Latent Sector Errors	545
44.3	Detecting Corruption: The Checksum	546
44.4	Using Checksums	549
44.5	A New Problem: Misdirected Writes	550
44.6	One Last Problem: Lost Writes	551
44.7	Scrubbing	551
44.8	Overheads Of Checksumming	552
44.9	Summary	552
	References	553
45	Summary Dialogue on Persistence	555
46	A Dialogue on Distribution	557
47	Distributed Systems	559
47.1	Communication Basics	560
47.2	Unreliable Communication Layers	561
47.3	Reliable Communication Layers	563
47.4	Communication Abstractions	565
47.5	Remote Procedure Call (RPC)	567
47.6	Summary	572
	References	573
48	Sun's Network File System (NFS)	575
48.1	A Basic Distributed File System	576
48.2	On To NFS	577
48.3	Focus: Simple and Fast Server Crash Recovery	577
48.4	Key To Fast Crash Recovery: Statelessness	578
48.5	The NFSv2 Protocol	579
48.6	From Protocol to Distributed File System	581
48.7	Handling Server Failure with Idempotent Operations	583

48.8	Improving Performance: Client-side Caching	585
48.9	The Cache Consistency Problem	585
48.10	Assessing NFS Cache Consistency	587
48.11	Implications on Server-Side Write Buffering	587
48.12	Summary	589
	References	590
49	The Andrew File System (AFS)	591
49.1	AFS Version 1	591
49.2	Problems with Version 1	592
49.3	Improving the Protocol	594
49.4	AFS Version 2	594
49.5	Cache Consistency	596
49.6	Crash Recovery	598
49.7	Scale And Performance Of AFSv2	598
49.8	AFS: Other Improvements	600
49.9	Summary	601
	References	603
	Homework	604
50	Summary Dialogue on Distribution	605
	General Index	607
	Asides	617
	Tips	619
	Cruces	621