
Contents

To Everyone	iii
To Educators	vi
To Students	viii
Acknowledgments	ix
Final Words	xiii
References	xiv
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	9
2.4 Persistence	11
2.5 Design Goals	13
2.6 Some History	14
2.7 Summary	19
References	20
Homework	21
I Virtualization	23
3 A Dialogue on Virtualization	25
4 The Abstraction: The Process	27
4.1 The Abstraction: A Process	28
4.2 Process API	29
4.3 Process Creation: A Little More Detail	30
4.4 Process States	31
4.5 Data Structures	33
4.6 Summary	35
References	37

Homework (Simulation)	38
5 Interlude: Process API	41
5.1 The <code>fork()</code> System Call	41
5.2 The <code>wait()</code> System Call	44
5.3 Finally, The <code>exec()</code> System Call	44
5.4 Why? Motivating The API	46
5.5 Process Control And Users	48
5.6 Useful Tools	49
5.7 Summary	50
References	52
Homework (Simulation)	53
Homework (Code)	54
6 Mechanism: Limited Direct Execution	57
6.1 Basic Technique: Limited Direct Execution	57
6.2 Problem #1: Restricted Operations	58
6.3 Problem #2: Switching Between Processes	63
6.4 Worried About Concurrency?	67
6.5 Summary	68
References	71
Homework (Measurement)	72
7 Scheduling: Introduction	73
7.1 Workload Assumptions	73
7.2 Scheduling Metrics	74
7.3 First In, First Out (FIFO)	74
7.4 Shortest Job First (SJF)	76
7.5 Shortest Time-to-Completion First (STCF)	77
7.6 A New Metric: Response Time	78
7.7 Round Robin	79
7.8 Incorporating I/O	81
7.9 No More Oracle	82
7.10 Summary	83
References	84
Homework (Simulation)	85
8 Scheduling:	
The Multi-Level Feedback Queue	87
8.1 MLFQ: Basic Rules	88
8.2 Attempt #1: How To Change Priority	89
8.3 Attempt #2: The Priority Boost	92
8.4 Attempt #3: Better Accounting	93
8.5 Tuning MLFQ And Other Issues	94
8.6 MLFQ: Summary	96
References	97
Homework (Simulation)	98

9 Scheduling: Proportional Share	99
9.1 Basic Concept: Tickets Represent Your Share	99
9.2 Ticket Mechanisms	101
9.3 Implementation	102
9.4 An Example	103
9.5 How To Assign Tickets?	104
9.6 Stride Scheduling	104
9.7 The Linux Completely Fair Scheduler (CFS)	105
9.8 Summary	110
References	111
Homework (Simulation)	112
10 Multiprocessor Scheduling (Advanced)	113
10.1 Background: Multiprocessor Architecture	114
10.2 Don't Forget Synchronization	116
10.3 One Final Issue: Cache Affinity	117
10.4 Single-Queue Scheduling	118
10.5 Multi-Queue Scheduling	119
10.6 Linux Multiprocessor Schedulers	122
10.7 Summary	122
References	123
Homework (Simulation)	124
11 Summary Dialogue on CPU Virtualization	127
12 A Dialogue on Memory Virtualization	129
13 The Abstraction: Address Spaces	131
13.1 Early Systems	131
13.2 Multiprogramming and Time Sharing	131
13.3 The Address Space	133
13.4 Goals	135
13.5 Summary	136
References	138
Homework (Code)	139
14 Interlude: Memory API	141
14.1 Types of Memory	141
14.2 The <code>malloc()</code> Call	142
14.3 The <code>free()</code> Call	144
14.4 Common Errors	144
14.5 Underlying OS Support	148
14.6 Other Calls	148
14.7 Summary	149
References	150
Homework (Code)	151

15 Mechanism: Address Translation	153
15.1 Assumptions	154
15.2 An Example	154
15.3 Dynamic (Hardware-based) Relocation	157
15.4 Hardware Support: A Summary	160
15.5 Operating System Issues	161
15.6 Summary	163
References	166
Homework (Simulation)	167
16 Segmentation	169
16.1 Segmentation: Generalized Base/Bounds	169
16.2 Which Segment Are We Referring To?	172
16.3 What About The Stack?	174
16.4 Support for Sharing	175
16.5 Fine-grained vs. Coarse-grained Segmentation	175
16.6 OS Support	176
16.7 Summary	178
References	179
Homework (Simulation)	180
17 Free-Space Management	181
17.1 Assumptions	182
17.2 Low-level Mechanisms	183
17.3 Basic Strategies	191
17.4 Other Approaches	193
17.5 Summary	195
References	197
Homework (Simulation)	198
18 Paging: Introduction	199
18.1 A Simple Example And Overview	199
18.2 Where Are Page Tables Stored?	203
18.3 What's Actually In The Page Table?	204
18.4 Paging: Also Too Slow	206
18.5 A Memory Trace	207
18.6 Summary	210
References	211
Homework (Simulation)	212
19 Paging: Faster Translations (TLBs)	215
19.1 TLB Basic Algorithm	216
19.2 Example: Accessing An Array	217
19.3 Who Handles The TLB Miss?	220
19.4 TLB Contents: What's In There?	222
19.5 TLB Issue: Context Switches	223
19.6 Issue: Replacement Policy	225

19.7 A Real TLB Entry	225
19.8 Summary	226
References	228
Homework (Measurement)	229
20 Paging: Smaller Tables	231
20.1 Simple Solution: Bigger Pages	231
20.2 Hybrid Approach: Paging and Segments	232
20.3 Multi-level Page Tables	235
20.4 Inverted Page Tables	243
20.5 Swapping the Page Tables to Disk	243
20.6 Summary	243
References	244
Homework (Simulation)	245
21 Beyond Physical Memory: Mechanisms	247
21.1 Swap Space	248
21.2 The Present Bit	249
21.3 The Page Fault	250
21.4 What If Memory Is Full?	251
21.5 Page Fault Control Flow	252
21.6 When Replacements Really Occur	253
21.7 Summary	254
References	255
Homework (Measurement)	256
22 Beyond Physical Memory: Policies	259
22.1 Cache Management	259
22.2 The Optimal Replacement Policy	260
22.3 A Simple Policy: FIFO	262
22.4 Another Simple Policy: Random	264
22.5 Using History: LRU	265
22.6 Workload Examples	266
22.7 Implementing Historical Algorithms	269
22.8 Approximating LRU	270
22.9 Considering Dirty Pages	271
22.10 Other VM Policies	272
22.11 Thrashing	272
22.12 Summary	273
References	274
Homework (Simulation)	276
23 Complete Virtual Memory Systems	277
23.1 VAX/VMS Virtual Memory	278
23.2 The Linux Virtual Memory System	284
23.3 Summary	293
References	295

24 Summary Dialogue on Memory Virtualization	297
II Concurrency	301
25 A Dialogue on Concurrency	303
26 Concurrency: An Introduction	305
26.1 Why Use Threads?	306
26.2 An Example: Thread Creation	307
26.3 Why It Gets Worse: Shared Data	310
26.4 The Heart Of The Problem: Uncontrolled Scheduling	313
26.5 The Wish For Atomicity	315
26.6 One More Problem: Waiting For Another	316
26.7 Summary: Why in OS Class?	317
References	318
Homework (Simulation)	319
27 Interlude: Thread API	321
27.1 Thread Creation	321
27.2 Thread Completion	322
27.3 Locks	325
27.4 Condition Variables	327
27.5 Compiling and Running	329
27.6 Summary	329
References	331
Homework (Code)	332
28 Locks	333
28.1 Locks: The Basic Idea	333
28.2 Pthread Locks	334
28.3 Building A Lock	335
28.4 Evaluating Locks	335
28.5 Controlling Interrupts	336
28.6 A Failed Attempt: Just Using Loads/Stores	337
28.7 Building Working Spin Locks with Test-And-Set	338
28.8 Evaluating Spin Locks	341
28.9 Compare-And-Swap	342
28.10 Load-Linked and Store-Conditional	343
28.11 Fetch-And-Add	344
28.12 Too Much Spinning: What Now?	345
28.13 A Simple Approach: Just Yield, Baby	346
28.14 Using Queues: Sleeping Instead Of Spinning	347
28.15 Different OS, Different Support	350
28.16 Two-Phase Locks	352
28.17 Summary	352
References	353

Homework (Simulation)	354
29 Lock-based Concurrent Data Structures	355
29.1 Concurrent Counters	355
29.2 Concurrent Linked Lists	361
29.3 Concurrent Queues	364
29.4 Concurrent Hash Table	366
29.5 Summary	366
References	369
Homework (Code)	370
30 Condition Variables	371
30.1 Definition and Routines	372
30.2 The Producer/Consumer (Bounded Buffer) Problem	376
30.3 Covering Conditions	384
30.4 Summary	386
References	387
Homework (Code)	388
31 Semaphores	391
31.1 Semaphores: A Definition	391
31.2 Binary Semaphores (Locks)	393
31.3 Semaphores For Ordering	394
31.4 The Producer/Consumer (Bounded Buffer) Problem	396
31.5 Reader-Writer Locks	401
31.6 The Dining Philosophers	403
31.7 Thread Throttling	406
31.8 How To Implement Semaphores	406
31.9 Summary	407
References	409
Homework (Code)	410
32 Common Concurrency Problems	411
32.1 What Types Of Bugs Exist?	411
32.2 Non-Deadlock Bugs	412
32.3 Deadlock Bugs	415
32.4 Summary	424
References	425
Homework (Code)	426
33 Event-based Concurrency (Advanced)	427
33.1 The Basic Idea: An Event Loop	427
33.2 An Important API: <code>select()</code> (or <code>poll()</code>)	428
33.3 Using <code>select()</code>	429
33.4 Why Simpler? No Locks Needed	431
33.5 A Problem: Blocking System Calls	431
33.6 A Solution: Asynchronous I/O	432

33.7 Another Problem: State Management	433
33.8 What Is Still Difficult With Events	435
33.9 Summary	436
References	437
Homework (Code)	438
34 Summary Dialogue on Concurrency	439
III Persistence	441
35 A Dialogue on Persistence	443
36 I/O Devices	445
36.1 System Architecture	445
36.2 A Canonical Device	447
36.3 The Canonical Protocol	448
36.4 Lowering CPU Overhead With Interrupts	449
36.5 More Efficient Data Movement With DMA	450
36.6 Methods Of Device Interaction	451
36.7 Fitting Into The OS: The Device Driver	452
36.8 Case Study: A Simple IDE Disk Driver	453
36.9 Historical Notes	455
36.10 Summary	457
References	458
37 Hard Disk Drives	459
37.1 The Interface	459
37.2 Basic Geometry	460
37.3 A Simple Disk Drive	461
37.4 I/O Time: Doing The Math	464
37.5 Disk Scheduling	468
37.6 Summary	472
References	473
Homework (Simulation)	474
38 Redundant Arrays of Inexpensive Disks (RAIDs)	475
38.1 Interface And RAID Internals	476
38.2 Fault Model	477
38.3 How To Evaluate A RAID	477
38.4 RAID Level 0: Striping	478
38.5 RAID Level 1: Mirroring	481
38.6 RAID Level 4: Saving Space With Parity	484
38.7 RAID Level 5: Rotating Parity	488
38.8 RAID Comparison: A Summary	489
38.9 Other Interesting RAID Issues	490
38.10 Summary	490

References	491
Homework (Simulation)	492
39 Interlude: Files and Directories	493
39.1 Files And Directories	493
39.2 The File System Interface	495
39.3 Creating Files	495
39.4 Reading And Writing Files	497
39.5 Reading And Writing, But Not Sequentially	499
39.6 Shared File Table Entries: <code>fork()</code> And <code>dup()</code>	501
39.7 Writing Immediately With <code>fsync()</code>	504
39.8 Renaming Files	504
39.9 Getting Information About Files	506
39.10 Removing Files	507
39.11 Making Directories	508
39.12 Reading Directories	509
39.13 Deleting Directories	510
39.14 Hard Links	510
39.15 Symbolic Links	512
39.16 Permission Bits And Access Control Lists	514
39.17 Making And Mounting A File System	516
39.18 Summary	518
References	520
Homework (Code)	521
40 File System Implementation	523
40.1 The Way To Think	523
40.2 Overall Organization	524
40.3 File Organization: The Inode	526
40.4 Directory Organization	530
40.5 Free Space Management	532
40.6 Access Paths: Reading and Writing	532
40.7 Caching and Buffering	536
40.8 Summary	538
References	539
Homework (Simulation)	540
41 Locality and The Fast File System	541
41.1 The Problem: Poor Performance	541
41.2 FFS: Disk Awareness Is The Solution	543
41.3 Organizing Structure: The Cylinder Group	543
41.4 Policies: How To Allocate Files and Directories	545
41.5 Measuring File Locality	547
41.6 The Large-File Exception	548
41.7 A Few Other Things About FFS	550
41.8 Summary	552
References	553

Homework (Simulation)	554
42 Crash Consistency: FSCK and Journaling	555
42.1 A Detailed Example	556
42.2 Solution #1: The File System Checker	559
42.3 Solution #2: Journaling (or Write-Ahead Logging)	561
42.4 Solution #3: Other Approaches	571
42.5 Summary	572
References	573
Homework (Simulation)	575
43 Log-structured File Systems	577
43.1 Writing To Disk Sequentially	578
43.2 Writing Sequentially And Effectively	579
43.3 How Much To Buffer?	580
43.4 Problem: Finding Inodes	581
43.5 Solution Through Indirection: The Inode Map	581
43.6 Completing The Solution: The Checkpoint Region	583
43.7 Reading A File From Disk: A Recap	583
43.8 What About Directories?	584
43.9 A New Problem: Garbage Collection	585
43.10 Determining Block Liveness	586
43.11 A Policy Question: Which Blocks To Clean, And When?	587
43.12 Crash Recovery And The Log	588
43.13 Summary	588
References	590
Homework (Simulation)	591
44 Flash-based SSDs	593
44.1 Storing a Single Bit	593
44.2 From Bits to Banks/Planes	594
44.3 Basic Flash Operations	595
44.4 Flash Performance And Reliability	597
44.5 From Raw Flash to Flash-Based SSDs	598
44.6 FTL Organization: A Bad Approach	599
44.7 A Log-Structured FTL	600
44.8 Garbage Collection	602
44.9 Mapping Table Size	604
44.10 Wear Leveling	609
44.11 SSD Performance And Cost	609
44.12 Summary	611
References	613
Homework (Simulation)	615
45 Data Integrity and Protection	617
45.1 Disk Failure Modes	617
45.2 Handling Latent Sector Errors	619

45.3	Detecting Corruption: The Checksum	620
45.4	Using Checksums	623
45.5	A New Problem: Misdirected Writes	624
45.6	One Last Problem: Lost Writes	625
45.7	Scrubbing	625
45.8	Overheads Of Checksumming	626
45.9	Summary	627
	References	628
	Homework (Simulation)	629
	Homework (Code)	630
46	Summary Dialogue on Persistence	631
47	A Dialogue on Distribution	633
48	Distributed Systems	635
48.1	Communication Basics	636
48.2	Unreliable Communication Layers	637
48.3	Reliable Communication Layers	639
48.4	Communication Abstractions	642
48.5	Remote Procedure Call (RPC)	643
48.6	Summary	648
	References	649
	Homework (Code)	650
49	Sun's Network File System (NFS)	653
49.1	A Basic Distributed File System	654
49.2	On To NFS	655
49.3	Focus: Simple And Fast Server Crash Recovery	655
49.4	Key To Fast Crash Recovery: Statelessness	656
49.5	The NFSv2 Protocol	657
49.6	From Protocol To Distributed File System	659
49.7	Handling Server Failure With Idempotent Operations	661
49.8	Improving Performance: Client-side Caching	663
49.9	The Cache Consistency Problem	663
49.10	Assessing NFS Cache Consistency	665
49.11	Implications On Server-Side Write Buffering	665
49.12	Summary	667
	References	669
	Homework (Measurement)	670
50	The Andrew File System (AFS)	671
50.1	AFS Version 1	671
50.2	Problems with Version 1	673
50.3	Improving the Protocol	674
50.4	AFS Version 2	674
50.5	Cache Consistency	676

50.6 Crash Recovery	678
50.7 Scale And Performance Of AFSv2	679
50.8 AFS: Other Improvements	681
50.9 Summary	682
References	683
Homework (Simulation)	684
51 Summary Dialogue on Distribution	685
General Index	687
Asides	699
Tips	703
Cruces	707