

M. H. Alsuwaiyel

Algorithms

Design Techniques
and Analysis

Second Edition

สำนักหอสมุด มหาวิทยาลัยเชียงใหม่

616705178

012576918

122685327

Lecture Notes Series on Computing - Vol. 15

Algorithms

Design Techniques and Analysis

Second Edition

M. H. Alsuwaiyel

King Fahd University of Petroleum & Minerals (KFUPM), Saudi Arabia



 World Scientific

NEW JERSEY • LONDON • SINGAPORE • BEIJING • SHANGHAI • HONG KONG • TAIPEI • CHENNAI • TOKYO

Contents

<i>Preface</i>	vii
<i>About the Author</i>	xi
<i>Acknowledgments</i>	xiii
Part 1 Basic Concepts and Introduction to Algorithms	1
Chapter 1 Basic Concepts in Algorithmic Analysis	3
1.1 Introduction	3
1.2 Historical Background	4
1.3 Binary Search	6
1.3.1 Analysis of the binary search algorithm	8
1.4 Merging Two Sorted Lists	10
1.5 Selection Sort	12
1.6 Insertion Sort	13
1.7 Bottom-Up Merge Sorting	15
1.7.1 Analysis of bottom-up merge sorting	17
1.8 Time Complexity	19
1.8.1 Order of growth	19
1.8.2 The O -notation	23
1.8.3 The Ω -notation	24
1.8.4 The Θ -notation	26
1.8.5 Examples	27
1.8.6 Complexity classes and the o -notation	30

1.9	Space Complexity	31
1.10	Optimal Algorithms	32
1.11	How to Estimate the Running Time of an Algorithm	33
1.11.1	Counting the number of iterations ^c	33
1.11.2	Counting the frequency of basic operations	39
1.11.3	Using recurrence relations	43
1.12	Worst Case and Average Case Analysis	44
1.12.1	Worst case analysis	45
1.12.2	Average case analysis	47
1.13	Amortized Analysis	48
1.14	Input Size and Problem Instance	52
1.15	Divide-and-Conquer Recurrences	54
1.15.1	Expanding the recurrence	54
1.15.2	Substitution	58
1.15.3	Change of variables	63
1.16	Practice Problems	66
1.17	Exercises	68
1.18	Bibliographic Notes	78
Chapter 2	Data Structures	79
2.1	Introduction	79
2.2	Linked Lists	79
2.2.1	Stacks and queues	80
2.3	Graphs	80
2.3.1	Representation of graphs	82
2.3.2	Planar graphs	83
2.4	Trees	84
2.5	Rooted Trees	84
2.5.1	Tree traversals	85
2.6	Binary Trees	85
2.6.1	Some quantitative aspects of binary trees . . .	87
2.6.2	Binary search trees	87
2.7	Practice Problems	88
2.8	Exercises	89
2.9	Bibliographic Notes	91

Chapter 3	Heaps and the Disjoint Sets Data Structures	93
3.1	Introduction	93
3.2	Heaps	93
3.2.1	Operations on heaps	95
3.2.1.1	Sift-up	95
3.2.1.2	Sift-down	96
3.2.1.3	Insert	97
3.2.1.4	Delete	98
3.2.1.5	Delete-max	98
3.2.2	Creating a heap	99
3.2.3	Heapsort	102
3.2.4	Min and max heaps	103
3.3	Disjoint Sets Data Structures	104
3.3.1	The union by rank heuristic	105
3.3.2	Path compression	107
3.3.3	The union-find algorithms	108
3.3.4	Analysis of the union-find algorithms	110
3.4	Practice Problems	112
3.5	Exercises	113
3.6	Bibliographic Notes	117
Part 2	Techniques Based on Recursion	119
Chapter 4	Induction	121
4.1	Introduction	121
4.2	Finding the Majority Element	122
4.3	Integer Exponentiation	123
4.4	Evaluating Polynomials (Horner's Rule)	124
4.5	Radix Sort	125
4.6	Generating Subsets of a Set	127
4.6.1	The first algorithm	128
4.6.2	The second algorithm	129
4.6.3	Iterative algorithm	131
4.7	Generating Permutations	133
4.7.1	The first algorithm	133
4.7.2	The second algorithm	135
4.7.3	Iterative algorithm	137

4.8	Practice Problems	139
4.9	Exercises	140
4.10	Bibliographic Notes	143
Chapter 5	Divide and Conquer	145
5.1	Introduction	145
5.2	Binary Search	147
	5.2.1 Analysis of the recursive binary search algorithm	147
5.3	Mergesort	149
	5.3.1 How the algorithm works	150
	5.3.2 Analysis of the mergesort algorithm	152
5.4	The Divide-and-Conquer Paradigm	154
5.5	Selection: Finding the Median and the k th Smallest Element	156
	5.5.1 Analysis of the selection algorithm	159
5.6	Quicksort	161
	5.6.1 A partitioning algorithm	162
	5.6.2 The sorting algorithm	164
	5.6.3 Analysis of the quicksort algorithm	166
	5.6.3.1 The worst case behavior	167
	5.6.3.2 The average case behavior	168
	5.6.4 Comparison of sorting algorithms	170
5.7	Quickselect	171
5.8	Multiselection	172
5.9	Multiplication of Large Integers	174
5.10	Matrix Multiplication	175
	5.10.1 The traditional algorithm	176
	5.10.2 Strassen's algorithm	176
	5.10.2.1 Time complexity	177
	5.10.3 Comparison of the two algorithms	177
5.11	The Closest Pair Problem	178
	5.11.1 Time complexity	181
5.12	A Dominance Problem	183
5.13	Practice Problems	184
5.14	Exercises	186
5.15	Bibliographic Notes	192

Chapter 6 Dynamic Programming	193
6.1 Introduction	193
6.2 The Longest Common Subsequence Problem	195
6.2.1 The algorithm	196
6.3 Matrix Chain Multiplication	198
6.3.1 The dynamic programming algorithm	201
6.4 The Dynamic Programming Paradigm	204
6.5 The All-Pairs Shortest Path Problem	205
6.5.1 The algorithm	205
6.6 The Knapsack Problem	207
6.6.1 The algorithm	208
6.7 Practice Problems	210
6.8 Exercises	211
6.9 Bibliographic Notes	215
Part 3 First-Cut Techniques	217
Chapter 7 The Greedy Approach	219
7.1 Introduction	219
7.2 The Shortest Path Problem	221
7.2.1 Implementation of the shortest path algorithm	223
7.2.2 Correctness	224
7.2.3 Time complexity	224
7.2.4 Improving the time bound	225
7.3 Minimum Cost Spanning Trees (Kruskal's Algorithm)	227
7.3.1 Implementation of Kruskal's algorithm	229
7.3.2 Correctness	229
7.3.3 Time complexity	230
7.4 Minimum Cost Spanning Trees (Prim's Algorithm)	231
7.4.1 Implementation of Prim's algorithm	232
7.4.2 Correctness	234
7.4.3 Time complexity	234
7.4.4 Improving the time bound	235

7.5	File Compression	237
7.5.1	The algorithm	238
7.5.2	Time complexity	239
7.6	Practice Problems	239
7.7	Exercises	240
7.8	Bibliographic Notes	244
Chapter 8	Graph Traversal	245
8.1	Introduction	245
8.2	Depth-First Search	245
8.2.1	The case of undirected graphs	247
8.2.2	The case of directed graphs	247
8.2.3	Time complexity of depth-first search	249
8.3	Applications of Depth-First Search	250
8.3.1	Graph acyclicity	250
8.3.2	Topological sorting	250
8.3.3	Finding articulation points in a graph	251
8.3.4	Strongly connected components	254
8.4	Breadth-First Search	255
8.4.1	Time complexity	257
8.5	Applications of Breadth-First Search	257
8.6	Practice Problems	258
8.7	Exercises	259
8.8	Bibliographic Notes	261
Part 4	Complexity of Problems	263
Chapter 9	NP-Complete Problems	265
9.1	Introduction	265
9.2	The Class P	268
9.3	The Class NP	269
9.4	NP-Complete Problems	271
9.4.1	The satisfiability problem	272
9.4.2	Proving NP-completeness	273
9.4.3	3-Satisfiability	275

9.4.4	Vertex cover, independent set and clique problems	276
9.4.5	More NP-complete problems	279
9.5	The Class co-NP	280
9.6	The Relationships between the Three Classes	282
9.7	Practice Problems	283
9.8	Exercises	284
9.9	Bibliographic Notes	285
Chapter 10 Introduction to Computational Complexity		287
10.1	Introduction	287
10.2	Model of Computation: The Turing Machine	287
10.3	k -Tape Turing Machines and Time Complexity	288
10.4	Off-line Turing Machines and Space Complexity	291
10.5	Tape Compression and Linear Speed-up	294
10.6	Relationships between Complexity Classes	295
10.6.1	Space and time hierarchy theorems	298
10.6.2	Padding arguments	300
10.7	Reductions	302
10.8	Completeness	306
10.8.1	NLOGSPACE-complete problems	307
10.8.2	PSPACE-complete problems	308
10.8.3	P-complete problems	309
10.8.4	Some conclusions of completeness	311
10.9	The Polynomial Time Hierarchy	313
10.10	Practice Problems	317
10.11	Exercises	318
10.12	Bibliographic Notes	321
Chapter 11 Lower Bounds		323
11.1	Introduction	323
11.2	Trivial Lower Bounds	323
11.3	The Decision Tree Model	324
11.3.1	The search problem	324
11.3.2	The sorting problem	325
11.3.3	Finding the maximum	327

11.3.4	Finding the largest and second largest elements	327
11.3.4.1	Lower bound	327
11.3.4.2	Optimal algorithm	328
11.4	The Algebraic Decision Tree Model	329
11.4.1	The element uniqueness problem	331
11.4.2	The set equality problem	332
11.4.3	The set inclusion problem	332
11.4.4	The set disjointness problem	333
11.5	Linear Time Reductions	333
11.5.1	The convex hull problem	334
11.5.2	The closest pair problem	335
11.5.3	The Euclidean minimum spanning tree problem	335
11.5.4	The diameter of a point set	336
11.6	Practice Problems	337
11.7	Exercises	337
11.8	Bibliographic Notes	339
Part 5 Coping with Hardness		341
Chapter 12 Backtracking		345
12.1	Introduction	345
12.2	The 3-Coloring Problem	345
12.2.1	The algorithm	347
12.3	The 8-Queens Problem	349
12.3.1	The algorithm	350
12.4	The General Backtracking Method	352
12.5	Branch and Bound	354
12.6	Practice Problems	359
12.7	Exercises	360
12.8	Bibliographic Notes	362
Chapter 13 Randomized Algorithms		363
13.1	Introduction	363
13.2	Las Vegas and Monte Carlo Algorithms	364

13.3	Two Simple Examples	365
13.3.1	A Monte Carlo algorithm	365
13.3.2	A Las Vegas algorithm	366
13.4	Randomized Quicksort	366
13.4.1	Expected running time of randomized quicksort	368
13.5	Randomized Quickselect	369
13.5.1	Expected running time of randomized quickselect	369
13.5.2	The dice problem	372
13.5.3	Application of the dice problem: Quickselect	374
13.6	Occupancy Problems	375
13.6.1	Number of balls in each bin	375
13.6.2	Number of empty bins	376
13.6.3	Balls falling into the same bin	377
13.6.4	Filling all bins	378
13.7	Tail Bounds	379
13.7.1	Markov inequality	379
13.7.2	Chebyshev inequality	380
13.7.3	Chernoff bounds	381
13.7.3.1	Lower tail	381
13.7.3.2	Upper tail	383
13.8	Application of Chernoff Bounds: Multiselection	384
13.8.1	Analysis of the algorithm	387
13.9	Random Sampling	390
13.10	The Min-Cut Problem	393
13.11	Testing String Equality	395
13.12	Pattern Matching	397
13.13	Primality Testing	400
13.14	Practice Problems	405
13.15	Exercises	406
13.16	Bibliographic Notes	409
Chapter 14	Approximation Algorithms	411
14.1	Introduction	411
14.2	Basic Definitions	411

14.3	Difference Bounds	413
14.3.1	Planar graph coloring	413
14.3.2	Hardness result: The knapsack problem	413
14.4	Relative Performance Bounds	414
14.4.1	The bin packing problem	415
14.4.2	The Euclidean traveling salesman problem	417
14.4.3	The vertex cover problem	419
14.4.4	Hardness result: The traveling salesman problem	420
14.5	Polynomial Approximation Schemes	422
14.5.1	The knapsack problem	422
14.6	Fully Polynomial Approximation Schemes	426
14.6.1	The subset-sum problem	426
14.7	Practice Problems	429
14.8	Exercises	429
14.9	Bibliographic Notes	432
Part 6	Iterative Improvement for Domain-Specific Problems	433
Chapter 15	Network Flow	435
15.1	Introduction	435
15.2	Preliminaries	435
15.3	The Ford–Fulkerson Method	439
15.4	Maximum Capacity Augmentation	440
15.5	Shortest Path Augmentation	442
15.6	Dinic’s Algorithm	445
15.7	The MPM Algorithm	448
15.8	Practice Problems	451
15.9	Exercises	451
15.10	Bibliographic Notes	453
Chapter 16	Matching	455
16.1	Introduction	455
16.2	Preliminaries	455

16.3	The Network Flow Method for Bipartite Graphs	458
16.4	The Hungarian Tree Method for Bipartite Graphs	459
16.5	Maximum Matching in General Graphs	462
16.6	An $O(n^{2.5})$ Algorithm for Bipartite Graphs	468
16.7	Practice Problems	473
16.8	Exercises	474
16.9	Bibliographic Notes	476

Part 7 Techniques in Computational Geometry 479

Chapter 17 Geometric Sweeping 481

17.1	Introduction	481
17.2	A Simple Example: Computing the Maximal Points of a Point Set	481
17.3	Geometric Preliminaries	483
17.4	Computing the Intersections of Line Segments	485
17.5	The Convex Hull Problem	489
17.6	Computing the Diameter of a Set of Points	492
17.7	Practice Problems	496
17.8	Exercises	497
17.9	Bibliographic Notes	499

Chapter 18 Voronoi Diagrams 501

18.1	Introduction	501
18.2	Nearest-Point Voronoi Diagram	501
18.2.1	Delaunay triangulation	504
18.2.2	Construction of the Voronoi diagram	506
18.3	Applications of the Voronoi Diagram	509
18.3.1	Computing the convex hull	509
18.3.2	All nearest neighbors	510
18.3.3	The Euclidean minimum spanning tree	511
18.4	Farthest-Point Voronoi Diagram	512
18.4.1	Construction of the farthest-point Voronoi dia- gram	513
18.5	Applications of the Farthest-Point Voronoi Diagram . .	515
18.5.1	All farthest neighbors	516
18.5.2	Smallest enclosing circle	516

18.6	Practice Problems	517
18.7	Exercises	517
18.8	Bibliographic Notes	519
Part 8 Techniques in Parallel Algorithms		521
Chapter 19 Parallel Algorithms		523
19.1	Introduction	523
19.1.1	Classifications of parallel architectures	525
19.2	Shared-Memory Computers (PRAM)	525
19.2.1	The balanced tree method	526
19.2.2	Brent theorem	528
19.2.3	Parallel prefix	529
19.2.3.1	Array packing	531
19.2.3.2	Parallel quicksort	532
19.2.4	Parallel search	533
19.2.5	Pointer jumping	535
19.2.6	Merging by ranking	536
19.2.6.1	Computing ranks	536
19.2.6.2	Merging	540
19.2.6.3	Parallel bottom-up merge sorting	540
19.2.7	The zero-one principle	541
19.2.8	Odd–even merging	542
19.2.9	Bitonic merging and sorting	546
19.2.9.1	Bitonic sorting	551
19.2.10	Pipelined merge sort	553
19.2.10.1	The algorithm	555
19.2.10.2	Maintaining ranks	557
19.2.10.3	Analysis of the algorithm	559
19.2.11	Selection	560
19.2.12	Multiselection	563
19.2.13	Matrix multiplication	567
19.2.14	Transitive closure	568
19.2.15	Shortest paths	569
19.2.16	Computing the convex hull of a set of points	569

19.3	Interconnection-Network Computers	574
19.4	The Hypercube	576
19.4.1	The butterfly	577
19.4.2	Embeddings of the hypercube	580
19.4.2.1	Gray codes	581
19.4.2.2	Embedding of a linear array into the hypercube	582
19.4.2.3	Embedding of a mesh into the hypercube	582
19.4.2.4	Embedding of a binary tree into the hypercube	583
19.4.3	Broadcasting on the hypercube	584
19.4.4	Permutation routing in the hypercube	584
19.4.4.1	The greedy algorithm	585
19.4.4.2	The randomized algorithm	585
19.4.5	Permutation routing in the butterfly	588
19.4.6	Computing parallel prefix on the hypercube	590
19.4.7	Hyperquicksort	591
19.4.8	Selection on the hypercube	593
19.4.9	Multiselection on the hypercube	594
19.4.10	Computing parallel prefix on the butterfly	597
19.5	The Linear Array and the Mesh	598
19.5.1	Broadcasting in the linear array and the mesh	599
19.5.2	Computing parallel prefix on the mesh	600
19.5.3	Odd–even transposition sort	601
19.5.4	Shearsort	602
19.5.5	Odd–even merging and sorting on the mesh .	604
19.5.6	Computing the convex hull of a set of points on the mesh	606
19.5.6.1	The first algorithm	607
19.5.6.2	The second algorithm	608

19.5.7	Three-dimensional mesh	612
19.5.7.1	Sorting on three-dimensional meshes	613
19.5.8	Fast Fourier transform	616
19.5.8.1	Implementation on the butterfly	618
19.5.8.2	Iterative FFT on the butterfly . .	620
19.5.8.3	The inverse Fourier transform . .	622
19.5.8.4	Applications of FFT	624
19.5.8.5	Product of polynomials	624
19.5.8.6	Computing the convolution of two vectors	626
19.6	Systolic Computation	627
19.6.1	An on-chip bubble sorter	627
19.7	Practice Problems	631
19.8	Exercises	634
19.9	Bibliographic Notes	640
19.10	Solutions	641
Appendix A. Mathematical Preliminaries		661
A.1	Sets, Relations and Functions	661
A.1.1	Sets	662
A.1.2	Relations	663
A.1.2.1	Equivalence relations	664
A.1.3	Functions	664
A.2	Proof Methods	665
A.2.1	Notation	665
A.2.2	Direct proof	666
A.2.3	Indirect proof	666
A.2.4	Proof by contradiction	666
A.2.5	Proof by counterexample	667
A.2.6	Mathematical induction	668
A.3	Logarithms	670
A.4	Floor and Ceiling Functions	671
A.5	Factorial and Binomial Coefficients	672
A.5.1	Factorials	672
A.5.2	Binomial coefficients	673

A.6	The Pigeonhole Principle	675
A.7	Summations	676
	A.7.1 Approximation of summations by integration	679
A.8	Recurrence Relations	682
	A.8.1 Solution of linear homogeneous recurrences	683
	A.8.2 Solution of inhomogeneous recurrences	685
A.9	Divide-and-Conquer Recurrences	688
A.10	Exercises	688
Appendix B. Introduction to Discrete Probability		691
B.1	Definitions	691
B.2	Conditional Probability and Independence	691
	B.2.1 Multiplication rule for conditional probability	693
B.3	Random Variables and Expectation	693
B.4	Discrete Probability Distributions	694
	B.4.1 Uniform distribution	694
	B.4.2 Bernoulli distribution	695
	B.4.3 Binomial distribution	695
	B.4.4 Geometric distribution	696
	B.4.5 Poisson distribution	696
<i>Bibliography</i>		697
<i>Index</i>		709