Thomas H. Cormen Charles E. Leiserson Ronald L. Rivest Clifford Stein

Introduction to Algorithms Fourth Edition

The MIT Press
Cambridge, Massachusetts London, England

Contents

Copyright

Preface

Foundations 1

Introduction

- The Role of Algorithms in Computing 1
 - Algorithms 1.1
 - Algorithms as a technology 1.2
- **Getting Started** 2
 - Insertion sort 2.1
 - Analyzing algorithms 2.2
 - 2.3 Designing algorithms
- **Characterizing Running Times** 3
 - O-notation, Ω -notation, and Θ -notation 3.1
 - Asymptotic notation: formal definitions 3.2
 - Standard notations and common functions 3.3
- Divide-and-Conquer 4
 - 4.1 Multiplying square matrices 4.2
 - Strassen's algorithm for matrix multiplication 4.3
 - The substitution method for solving recurrences The recursion-tree method for solving 4.4 recurrences

- 4.5 The master method for solving recurrences
- ★ 4.6 Proof of the continuous master theorem
- ★ 4.7 Akra-Bazzi recurrences

5 Probabilistic Analysis and Randomized Algorithms

- 5.1 The hiring problem
- 5.2 Indicator random variables
- 5.3 Randomized algorithms
- ★ 5.4 Probabilistic analysis and further uses of indicator random variables

II Sorting and Order Statistics

Introduction

6 Heapsort

- 6.1 Heaps
- 6.2 Maintaining the heap property
- 6.3 Building a heap
- 6.4 The heapsort algorithm
- 6.5 Priority queues

7 Quicksort

- 7.1 Description of quicksort
- 7.2 Performance of quicksort
- 7.3 A randomized version of quicksort
- 7.4 Analysis of quicksort

8 Sorting in Linear Time

- 8.1 Lower bounds for sorting
- 8.2 Counting sort
- 8.3 Radix sort
- 8.4 Bucket sort

9 Medians and Order Statistics

- 9.1 Minimum and maximum
- 9.2 Selection in expected linear time
- 9.3 Selection in worst-case linear time

III Data Structures

Introduction

10 Elementary Data Structures

- Simple array-based data structures: arrays, 10.1 matrices, stacks, queues
- 10.2 Linked lists
- Representing rooted trees 10.3

11 Hash Tables

- 11.1 Direct-address tables
- 11.2 Hash tables
- 11.3 Hash functions
- 11.4 Open addressing
- 11.5 Practical considerations

12 Binary Search Trees

- 12.1 What is a binary search tree?
- 12.2 Querying a binary search tree +
- 12.3 Insertion and deletion

13 Red-Black Trees

- 13.1 Properties of red-black trees
- 13.2 Rotations
- 13.3 Insertion
- 13.4 Deletion

Advanced Design and Analysis Techniques IV

Introduction

14 Dynamic Programming

- 14.1 Rod cutting
- 14.2 Matrix-chain multiplication 14.3
- Elements of dynamic programming 14.4
- Longest common subsequence 14.5 Optimal binary search trees
- 15 Greedy Algorithms

- 15.1 An activity-selection problem
- 15.2 Elements of the greedy strategy
- 15.3 Huffman codes
- 15.4 Offline caching

16 Amortized Analysis

- 16.1 Aggregate analysis
- 16.2 The accounting method
- 16.3 The potential method
- 16.4 Dynamic tables

V Advanced Data Structures

Introduction

17 Augmenting Data Structures

- 17.1 Dynamic order statistics
- 17.2 How to augment a data structure
- 17.3 Interval trees

18 B-Trees

- 18.1 Definition of B-trees
- 18.2 Basic operations on B-trees
- 18.3 Deleting a key from a B-tree

19 Data Structures for Disjoint Sets

- 19.1 Disjoint-set operations
- 19.2 Linked-list representation of disjoint sets
- 19.3 Disjoint-set forests
- ★ 19.4 Analysis of union by rank with path compression

VI Graph Algorithms

Introduction

20 Elementary Graph Algorithms

- 20.1 Representations of graphs
- 20.2 Breadth-first search

	20.3	Depth-first search
	201	Topological sort
	20.5	Strongly connected components
21	Mini	mum Spanning Trees Growing a minimum spanning tree The algorithms of Kruskal and Prim
22	Sing 22.1 22.2 22.3 22.4	le-Source Shortest Paths The Bellman-Ford algorithm Single-source shortest paths in directed acyclic graphs Dijkstra's algorithm Difference constraints and shortest paths Proofs of shortest-paths properties
2	3 All-	Pairs Shortest Paths
	23.1	Shortest paths and matrix multiplication
	23.2	The Floyd-Warshall algorithm
	23.3	Johnson's algorithm for sparse graphs
2	4 Ma	aximum Flow
	24.1	Flow networks
	24.2	The Ford-Fulkerson method
	24.3	Maximum bipartite matching
2	25 M	atchings in Bipartite Graphs
	25.1	Maximum hipartite made 1
	25.2	Maximum bipartite matching (revisited) The stable-marriage problem
	25.3	The Hungarian algorithm for the assignment problem
ecte	d Topi	CS

VII Selecte

Introduction

Parallel Algorithms 26.1

The basics of fork-join parallelism 26.2 Parallel matrix multiplication

Parallel merge sort 26.3

27 Online Algorithms

- 27.1 Waiting for an elevator
- 27.2 Maintaining a search list
- Online caching 27.3

Matrix Operations 28

- Solving systems of linear equations 28.1
- 28.2 Inverting matrices
- Symmetric positive-definite matrices and least-28.3 squares approximation

29 Linear Programming

- Linear programming formulations and 29.1 algorithms
- Formulating problems as linear programs 29.2
- Duality 29.3

30 Polynomials and the FFT

- Representing polynomials 30.1
- The DFT and FFT 30.2
- FFT circuits 30.3

31 Number-Theoretic Algorithms

- Elementary number-theoretic notions 31.1
- Greatest common divisor 31.2
- 31.3 Modular arithmetic
- 31.4 Solving modular linear equations
 - 31.5 The Chinese remainder theorem
 - 31.6 Powers of an element
 - The RSA public-key cryptosystem 31.7
- Primality testing 31.8

String Matching 32

- The naive string-matching algorithm 32.1
- 32.2 The Rabin-Karp algorithm
- String matching with finite automata 32.3
- The Knuth-Morris-Pratt algorithm 32.4

32.5	Suffix	arrays
------	--------	--------

33 Machine-Learning Algorithms

- 33.1 Clustering
- Multiplicative-weights algorithms 33.2
- Gradient descent 33.3

34 NP-Completeness

- Polynomial time 34.1
- Polynomial-time verification 34.2
- NP-completeness and reducibility 34.3
- NP-completeness proofs 34.4
- NP-complete problems 34.5

Approximation Algorithms 35

- The vertex-cover problem 35.1
- 35.2 The traveling-salesperson problem
- 35.3 The set-covering problem
- Randomization and linear programming 35.4
- 35.5 The subset-sum problem

VIII Appendix: Mathematical Background

Introduction

Summations

- Summation formulas and properties
- A.2 Bounding summations

B Sets, Etc.

- **B**.1 Sets
- **B.2** Relations
- **B.3 Functions**
- **B.4** Graphs
- **B.5** Trees

Counting and Probability

- Counting
- C.2 Probability

- C.3 Discrete random variables
- C.4 The geometric and binomial distributions
- ★ C.5 The tails of the binomial distribution
- **D** Matrices
 - D.1 Matrices and matrix operations
 - D.2 Basic matrix properties

Bibliography

Index