- [1] E. H. L. Aarts and J. Korst. Simulated Annealing and Boltzmann Machines. Wiley, 1989.
- [2] J. Abello, A. Buchsbaum, and J. Westbrook. A functional approach to external graph algorithms. *Algorithmica*, 32(3):437–458, 2002.
- [3] W. Ackermann. Zum hilbertschen Aufbau der reellen Zahlen. Mathematische Annalen, 99:118–133, 1928.
- [4] G. M. Adel'son-Vel'skii and E. M. Landis. An algorithm for the organization of information. Soviet Mathematics Doklady, 3:1259–1263, 1962.
- [5] A. Aggarwal and J. S. Vitter. The input/output complexity of sorting and related problems. *Communications of the ACM*, \$1(9):1116–1127, 1988.

  [6] A. V. Aho, J. E. Hopcroft, and J. D. Ullman. *The Design and Analysis of*
- Computer Algorithms. Addison-Wesley, 1974.
- [7] A. V. Aho, B. W. Kernighan, and P.J. Weinberger. The AWK Programming Language. Addison-Wesley, 1988.
- [8] R. K. Ahuja, R. L. Magnanti, and J. B. Orlin. Network Plows. Prentice Hall, 1993.
- [9] R. K. Ahuja, K. Mehlhorn, J. B. Orlin, and R. E. Tarjan. Faster algorithms for the shortest path problem. *Journal of the ACM*, 3(2):213–223, 1990.
- [10] N. Alon, M. Dietzfelbinger, P. B. Miltersen, E. Petrank, and E. Tardos. Linear hash functions. *Journal of the ACM*, 46(5):667,683, 1999.
- [11] A. Andersson, T. Hagerup, S. Nilsson, and R. Raman. Sorting in linear time? Journal of Computer and System Sciences, 57(1):74–93, 1998.
- [12] F. Annexstein, M. Baumslag, and A. Rosenberg. Group action graphs and parallel architectures. SIAM Journal on Computing, 19(3):544–569, 1990.
- [13] D. L. Applegate, R. E. Bixby, V. Chvátal, and W. J. Cook. *The Traveling* Salesman Problem: A Computational Study. Princeton University Press, 2007.
- [14] G. Ausiello, P. Crescenzi, G. Gambosi, V. Kann, A. Marchetti-Spaccamela, and M. Protasi. Complexity and Approximation: Combinatorial Optimization Problems and Their Approximability Properties. Springer, 1999.
- [15] H. Bast, S. Funke, P. Sanders, and D. Schultes. Fast routing in road networks with transit nodes. Science, 316(5824):566, 2007.

- [16] R. Bayer and E. M. McCreight. Organization and maintenance of large ordered indexes. *Acta Informatica*, 1(3):173–189, 1972.
- [17] R. Beier and B. Vöcking. Random knapsack in expected polynomial time. *Journal of Computer and System Sciences*, 69(3):306–329, 2004.
- [18] R. Bellman. On a routing problem. *Quarterly of Applied Mathematics*, 16(1):87–90, 1958.
- [19] M. A. Bender, E. D. Demaine, and M. Farach-Colton. Cache-oblivious B-trees. In 41st Annual Symposium on Foundations of Computer Science, pages 399 409, 2000.
- [20] J. L. Rentley and M. D. McIlroy. Engineering a sort function. *Software Practice and Experience*, 23(11):1249–1265, 1993.
- [21] J. L. Bendey and T. A. Ottmann. Algorithms for reporting and counting geometric intersections. *IEEE Transactions on Computers*, pages 643–647, 1979.
- [22] J. L. Bentley and R. Sedgewick. Fast algorithms for sorting and searching strings. In 8th Annual ACM-SIAM Symposium on Discrete Algorithms, pages 360–369, 1997.
- [23] D. Bertsimas and J. N. Tsitsiklis. *Introduction to Linear Optimization*. Athena Scientific, 1997.
- [24] G. E. Blelloch, C. E. Leiserson, B. M. Maggs, C. G. Plaxton, S. J. Smith, and M. Zagha. A comparison of sorting algorithms for the connection machine CM-2. In 3rd ACM Symposium on Parallel Algorithms and Architectures, pages 3–16, 1991.
- [25] M. Blum, R. W. Floyd, V. R. Pratt, R. L. Rivest, and R. E. Tarjan. Time bounds for selection. *Journal of Computer and System Sciences*, 7(4):448, 1972.
- [26] N. Blum and K. Mehlhorn. On the average number of rebalancing operations in weight-balanced trees. *Theoretical Computer Science*, 11:303–320, 1980.
- [27] Boost.org. Boost C++ Libraries. www.boost.org.
- [28] O. Boruvka. O jistém problému minimálním. *Pràce, Moravské Prirodovedecké Spolecnosti*, pages 1–58, 1926.
- [29] F. C. Botelho, R. Pagh, and N. Ziviani. Simple and space-efficient minimal perfect hash functions. In *10th Workshop on Algorithms and Data Structures*, volume 4619 of Lecture Notes in Computer Science, pages 139–150. Springer, 2007.
- [30] G. S. Brodal. Worst-case efficient priority queues. In 7th Annual ACM-SIAM Symposium on Discrete Algorithms, pages 52–58, 1996.
- [31] G. S. Brodal and J. Katajainen. Worst-case efficient external-memory priority queues. In *6th Scandinavian Workshop on Algorithm Theory*, volume 1432 of Lecture Notes in Computer Science, pages 107–118. Springer, 1998.
- [32] M. R. Brown and R. E. Tarjan. Design and analysis of a data structure for representing sorted lists. *SIAM Journal of Computing*, 9:394–614, 1980.
- [33] R. Brown. Calendar queues: A fast O(1) priority queue in plementation for the simulation event set problem. *Communications of the ACM*, 31(10):1220–1227, 1988.
- [34] J. L. Carter and M. N. Wegman. Universal classes of hash functions. *Journal of Computer and System Sciences*, 18(2):143–154, Apr. 1979.

- [35] B. Chazelle. A minimum spanning tree algorithm with inverse-Ackermann type complexity. *Journal of the ACM*, 47:1028–1047, 2000.
- [36] B. Chazelle and L. J. Guibas. Fractional cascading: I. A data structuring technique. *Algorithmica*, 1(2):133–162, 1986.
- [37] B. Chazelle and L. J. Guibas. Fractional cascading: II. Applications. *Algorithmica*, 1(2):463–191, 1986.
- [38] J.-C. Chen. Proportion extend sort. *SIAM Journal on Computing*, 31(1):323–330, 2001.
- [39] J. Cheriyan and K. Mehlhorn. Algorithms for dense graphs and networks. *Algorithmica*, 15(6):521–549, 1996.
- [40] B. V. Cherkassky, A. V. Goldberg, and T. Radzik. Shortest path algorithms: Theory and experimental evaluation. *Mathematical Programming*, 73:129–174, 1996.
- [41] E. G. Coffman, M. R. Garey, and D. S. Johnson. Approximation algorithms for bin packing: A survey. In D. Hochbaum, editor, *Approximation Algorithms for NP-Hard Problems*, pages 46–93. PWS, 1997.
- [42] D. Cohen-Or, D. Levin, and O. Remez. Progressive compression of arbitrary triangular meshes. In *IEEE Conference on Visualization*, pages 67–72, 1999.
- [43] S. A. Cook. *On the Minimum Computation Time of Functions*. PhD thesis, Harvard University, 1966.
- [44] S. A. Cook. The complexity of theorem proving procedures. In *3rd ACM Symposium on Theory of Computing*, pages 151–158, 1971.
- [45] G. B. Dantzig. Maximization of a linear function of variables subject to linear inequalities. In T. C. Koopmans, editor, *Activity Analysis of Production and Allocation*, pages 339–347. Wiley, 1951.
- [46] M. de Berg, M. van Kreveld, M. Overmars, and O. Schwarzkopf. *Computational Geometry Algorithms and Applications*. Springer, 2nd edition, 2000.
- [47] R. Dementiev, L. Kettner, J. Mehnert, and P. Sanders. Engineering a sorted list data structure for 32 bit keys. In 6th Workshop on Algorithm Engineering & Experiments, New Orleans, 2004.
- [48] R. Dementiev, L. Kettner, and P. Sanders. STXXL: Standard Template Library for XXL data sets. *Software: Practice and Experience*, 2007. To appear, see also http://stxxl.sourceforge.net/.
- [49] R. Dementiev and P. Sanders. Asynchronous parallel disk sorting. In 15th ACM Symposium on Parallelism in Algorithms and Architectures, pages 138–148, San Diego, 2003.
- [50] R. Dementiev, P. Sanders, D. Schultes, and J. Sibeyn. Engineering an external memory minimum spanning tree algorithm. In *IFIP TCS*, Toulouse, 2004.
- [51] L. Devroye. A note on the height of binary search trees. *Journal of the ACM*, 33:289–498, 1986.
- [52] R. B. Dial. Shortest-path forest with topological ordering. *Communications of the ACM*, 12(11):632–633, 1969.
- [53] M. Dietzfelbinger, T. Hagerup, J. Katajainen, and M. Penttonen. A reliable randomized algorithm for the closest-pair problem. *Journal of Algorithms*, 1(25):19–51, 1997.

- [54] M. Dietzfelbinger, A. Karlin, K. Mehlhorn, F. Meyer auf der Heide, H. Rohnert, and R. E. Tarjan. Dynamic perfect hashing: Upper and lower bounds. *SIAM Journal of Computing*, 23(4):738–761, 1994.
- [55] M. Dietzfelbinger and C. Weidling. Balanced allocation and dictionaries with tightly packed constant size bins. *Theoretical Computer Science*, 380(1–2):47–63, 2007.
- [56] E. W. Dijkstra, A note on two problems in connexion with graphs. *Numerische Mathematik*, 1:269–271, 1959.
- [57] E. A. Dinic. Economical algorithms for finding shortest paths in a network. In *Transportation Modeling Systems*, pages 36–44, 1978.
- [58] W. Domschke and A. Drexl. Einführung in Operations Research. Springer, 2007.
- [59] J. R. Driscoll, N. Sarnak, D. D. Sleator, and R. E. Tarjan. Making data structures persistent. *Journal of Computer and System Sciences*, 38(1):86–124, 1989.
- [60] J. Fakcharoenphol and S. Rao. Planar graphs, negative weight edges, shortest paths, and near linear time. *Journal of Computer and System Sciences*, 72(5):868–889, 2006.
- [61] R. Fleischer. A tight lower bound for the worst case of Bottom-Up-Heapsort. *Algorithmica*, 11(2):104–115, 1994.
- [62] R. Floyd. Assigning meaning to programs. In J. Schwarz, editor, *Mathematical Aspects of Computer Science*, pages 19–32. AMS, 1967.
- [63] L. R. Ford. Network flow theory. Technical Report P-923, Rand Corporation, Santa Monica, California, 1956.
- [64] E. Fredkin. Trie memory. Communications of the ACM, 3:490–499, 1960.
- [65] M. L. Fredman. On the efficiency of pairing heaps and related data structures. *Journal of the ACM*, 46(4):473–501, 1999.
- [66] M. L. Fredman, J. Komlos, and E. Szemeredi. Storing a sparse table with O(1) worst case access time. *Journal of the ACM*, 31:538–544, 1984.
- [67] M. L. Fredman, R. Sedgewick, D. D. Sleator, and R. E. Tarjan. The pairing heap: A new form of self-adjusting heap. Algorithmica, 1:111–129, 1986.
- [68] M. L. Fredman and R. E. Tarjan. Fibonacch heaps and their uses in improved network optimization algorithms. *Journal of the ACM*, 34:596–615, 1987.
- [69] M. Frigo, C. E. Leiserson, H. Prokop, and S. Ramachandran. Cache-oblivious algorithms. In *40th IEEE Symposium on Foundations of Computer Science*, pages 285–298, 1999.
- [70] H. N. Gabow. Path-based depth-first search for strong and biconnected components. *Information Processing Letters*, pages 107–114, 2000.
- [71] E. Gamma, R. Helm, R. Johnson, and J. Vlissides. *Design Patterns: Elements of Reusable Object-Oriented Software*. Addison-Wesley, 1995.
- [72] M. R. Garey and D. S. Johnson. *Computers and Intractability: A Guide to the Theory of NP-Completeness*. W. H. Freeman, 1979.
- [73] B. Gärtner and J. Matousek. *Understanding and Using Linear Programming*. Springer, 2006.

- [74] GMP (GNU Multiple Precision Arithmetic Library). http://gmplib.org/.
- [75] A. V. Goldberg. Scaling algorithms for the shortest path problem. *SIAM Journal on Computing*, 24:494–504, 1995.
- [76] A. V. Goldberg. A simple shortest path algorithm with linear average time. In 9th European Symposium on Algorithms, volume 2161 of Lecture Notes in Computer Science, pages 230–241. Springer, 2001.
- [77] A. V. Goldberg and C. Harrelson. Computing the shortest path: A\* meets graph theory. In 16th Annual ACM-SIAM Symposium on Discrete Algorithms, pages 156–165, 2005.
- [78] M. T. Goodrich and R. Tamassia. JDSL the data structures library in Java. http://www.jdsl.org/.
- [79] G. Graefe and P.-A. Larson. B-tree indexes and CPU caches. In 17th International Conference on Data Engineering, pages 349–358. IEEE, 2001.
- [80] R. L. Graham. Bounds for certain multiprocessing anomalies. *Bell System Technical Journal*, 45:1563–1581, 1966.
- [81] R. L. Graham, D. E. Knuth, and O. Patashnik. *Concrete Mathematics*. Addison-Wesley, 2nd edition, 1994.
- [82] J. F. Grantham and C. Pomerance. Prime numbers. In K. H. Rosen, editor, *Handbook of Discrete and Combinatorial Mathematics*, chapter 4.4, pages 236–254. CRC Press, 2000.
- [83] R. Grossi and G. Italiano. Efficient techniques for maintaining multidimensional keys in linked data structures. In 26th International Colloquium on Automata, Languages and Programming, volume 1644 of Lecture Notes in Computer Science, pages 372–381. Springer, 1999.
- [84] S. Halperin and U. Zwick. Optimal randomized EREW PRAM algorithms for finding spanning forests and for other basic graph connectivity problems. In 7th Annual ACM-SIAM Symposium on Discrete Algorithms, pages 438–447, 1996.
- [85] Y. Han and M. Thorup. Integer sorting in  $O(n\sqrt{\log\log n})$  expected time and linear space. In 42nd IEEE Symposium on Foundations of Computer Science, pages 135–144, 2002.
- [86] G. Handler and I. Zang. A dual algorithm for the constrained shortest path problem. *Networks*, 10:293–309, 1980.
- [87] J. Hartmanis and J. Simon. On the power of multiplication in random access machines. In *5th IEEE Symposium on Foundations of Computer Science*, pages 13–23, 1974.
- [88] M. Held and R. Karp. The traveling-salesman problem and minimum spanning trees. *Operations Research*, 18:1138–1162, 1970.
- [89] M. Held and R. Karp. The traveling-salesman problem and minimum spanning trees, part II. *Mathematical Programming*, 1:6–25, 1971.
- [90] P. V. Hentenryck and L. Michel. *Constraint-Based Local Search*. MIT Press, 2005.
- [91] C. A. R. Hoare. An axiomatic basis for computer programming. *Communications of the ACM*, 12:576–585, 1969.

- [92] C. A. R. Hoare. Proof of correctness of data representations. *Acta Informatica*, 1:271–281, 1972.
- [93] R. D. Hofstadter. Metamagical themas. *Scientific American*, pages 16–22, January 1983.
- [94] P. Høyer. A general technique for implementation of efficient priority queues. In 3rd Israeli Symposium on Theory of Computing and Systems, pages 57–66, 1995.
- [95] S. Huddlestone and K. Mehlhorn. A new data structure for representing sorted lists. *Acta Informatica*, 17:157–184, 1982.
- [96] J. Iacono. Improved upper bounds for pairing heaps. In 7th Scandinavian Workshop on Algorithm Theory, volume 1851 of Lecture Notes in Computer Science, pages 32–45. Springer, 2000.
- [97] A. Itai, A. G. Konheim, and M. Rodeh. A sparse table implementation of priority queues. In 8th International Colloquium on Automata, Languages and Programming, volume 115 of Lecture Notes in Computer Science, pages 417–431. Springer, 1981.
- [98] V. Jarník. O jistém problému minimálním. *Práca Moravské Přírodovědecké Společnosti*, 6:57–63, 1930.
- [99] K. Jensen and N. Wirth. *Pascal User Manual and Report: ISO Pascal Standard*. Springer, 1991.
- [100] T. Jiang, M. Li, and P. Vitányi. Average-case complexity of shellsort. In 26th International Colloquium on Automata, Languages and Programming, volume 1644 of Lecture Notes in Computer Science, pages 453–462. Springer, 1999.
- [101] D. S. Johnson, C. R. Aragon, L. A. McGeoch, and C. Schevon. Optimization by simulated annealing: Experimental evaluation, part II, graph coloring and number partitioning. *Operations Research*, 39(3):378–406, 1991.
- [102] K. Kaligosi and P. Sanders. How branch mispredictions affect quicksort. In *14th European Symposium on Algorithms*, volume 4168 of Lecture Notes in Computer Science, pages 780–791. Springer, 2006.
- [103] H. Kaplan and R. E. Tarjan. New heap data structures. Technical Report TR-597-99, Princeton University, 1999.
- [104] A. Karatsuba and Y. Ofman. Multiplication of multidigit numbers on automata. *Soviet Physics Doklady*, 7(7):595–596, 1963.
- [105] D. Karger, P. N. Klein, and R. E. Tarjan. A randomized linear-time algorithm for finding minimum spanning trees. *Journal of the ACM*, 42:321–329, 1995.
- [106] N. Karmakar. A new polynomial-time algorithm for linear programming. *Combinatorica*, pages 373–395, 1984.
- [107] J. Katajainen and B. B. Mortensen. Experiences with the design and implementation of space-efficient deque. In *Workshop on Algorithm Engineering*, volume 2141 of Lecture Notes in Computer Science, pages 39–50. Springer, 2001.
- [108] I. Katriel, P. Sanders, and J. L. Träff. A practical minimum spanning tree algorithm using the cycle property. Technical Report MPI-I-2002-1-003, MPI Informatik, Germany, October 2002.

- [109] H. Kellerer, U. Pferschy, and D. Pisinger. Knapsack Problems. Springer, 2004.
- [110] L. Khachiyan. A polynomial time algorithm in linear programming. Soviet Mathematics Doklady, 20(1):191–194, 1979.
- [111] V. King. A simpler minimum spanning tree verification algorithm. Algorithmica, 18:263–270, 1997.
  [112] D. E. Knuth. The Art of Computer Programming: Sorting and Searching,
- volume 3. Addison-Wesley, 2nd edition, 1998.
- [113] D. E. Knuth. MMIXware: A RISC Computer for the Third Millennium, volume 1750 of Lecture Notes in Computer Science. Springer, 1999.
- [114] R. E. Korf. Depth-first iterative-deepening: An optimal admissible tree search. Artificial Intelligence, 27 97–109, 1985.
- [115] B. Korte and J.Vygen. Combinatorial Optimization: Theory and Algorithms. Springer, 2000.
- [116] J. Kruskal. On the shortest spanning subtree of a graph and the traveling salesman problem. Proceedings of the American Mathematical Society, 7:48-50, 1956.
- [117] E. L. Lawler, J. K. Lenstra, A. H. G. Rinooy Kan, and D. B. Shmoys. *The* Traveling Salesman Problem. Wiley, 1985.
- [118] LEDA (Library of Efficient Data Types and Algorithms). www. algorithmic-solutions.com.
- [119] L. Q. Lee, A. Lumsdaine, and J. G. Siek. The Boost Graph Library: User Guide and Reference Manual. Addison-Wesley, 2002.
- [120] L. Levin. Universal search problems. Problemy Peredachi Informatsii, 9(3):265–266, 1973.
- [121] I. Lustig and J.-F. Puget. Program does not equal program: Constraint programming and its relationship to mathematical programming. *Interfaces*, 31:29-53, 2001.
- [122] S. Martello and P. Toth. Knapsack Problems: Algorithms and Computer Implementations. Wiley, 1990.
- [123] C. Martínez and S. Roura. Optimal sampling strategies in Quicksort and Quickselect. SIAM Journal on Computing, 31(3):683-705, 2002.
- [124] C. McGeoch, P. Sanders, R. Fleischer, P. R. Cohen, and D. Precup. Using finite experiments to study asymptotic performance. In Experimental Algorithmics — From Algorithm Design to Robust and Efficient Software, volume 2547 of Lecture Notes in Computer Science, pages 1–23. Springer, 2002.
- [125] MCSTL: The Multi-Core Standard Template Library. http://algo2. iti.uni-karlsruhe.de/singler/mcstl/.
- [126] K. Mehlhorn. A faster approximation algorithm for the Steiner problem in graphs. *Information Processing Letters*, 27(3):125–128, Mar. 1988.
- [127] K. Mehlhorn. Amortisierte Analyse. In T. Ottmann, editor, Prinzipien des Algorithmenentwurfs, pages 91–102. Spektrum Lehrbuch, 1998.
- [128] K. Mehlhorn and U. Meyer. External memory breadth-first search with sublinear I/O. In 10th European Symposium on Algorithms, volume 2461 of Lecture Notes in Computer Science, pages 723–735. Springer, 2002.

- [129] K. Mehlhorn and S. Näher. Bounded ordered dictionaries in  $O(\log \log N)$  time and O(n) space. Information Processing Letters, 35(4):183–189, 1990.
- [130] K. Mehlhorn and S. Näher. Dynamic fractional cascading. Algorithmica, 5:215-241, 1990.
- [131] K. Mehlhorn and S. Näher. The LEDA Platform for Combinatorial and Geo-
- metric Computing. Cambridge University Press, 1999. [132] K. Mehlhorn, S. Näher, and P. Sanders. Engineering DFS-based graph algorithms. Submitted, 2007.
- [133] K. Mehlhorn, V. Priebe, G. Schäfer, and N. Sivadasan. All-pairs shortestpaths computation in the presence of negative cycles. *Information Processing Letters*, 81(6):341–343, 2002.
- [134] K. Mehlhorn and P. Sanders, Scanning multiple sequences via cache memory. Algorithmica, 35(1):75–93, 2003.
- [135] K. Mehlhorn and M. Ziegelmann. Resource constrained shortest paths. In 8th European Symposium on Algorithms, volume 1879 of Lecture Notes in Computer Science, pages 326–337, 2000.
- [136] R. Mendelson, R. E. Tarjan, M. Thorup, and U. Zwick. Melding priority queues. In 9th Scandinavian Workshop on Algorithm Theory, pages 223–235,
- [137] Meyers Konversationslexikon. Bibliographisches Institut, 1888.
- [138] B. Meyer. Object-Oriented Software Construction. Prentice Hall, 2nd edition,
- [139] U. Meyer. Average-case complexity of single-source shortest-path algorithms: Lower and upper bounds. *Journal of Algorithms*, 48(1):91–134, 2003.
- [140] U. Meyer and P. Sanders.  $\Delta$ -stepping: A parallel shortest path algorithm. In 6th European Symposium on Algorithms, number 1461 in Lecture Notes in Computer Science, pages 393–404. Springer, 1998.
- [141] U. Meyer, P. Sanders, and J. Sibeyn, editors. Algorithms for Memory Hierarchies, volume 2625 of Lecture Notes in Computer Science. Springer, 2003.
- [142] B. M. E. Moret and H. D. Shapiro. An empirical analysis of algorithms for constructing a minimum spanning tree. In 2nd Workshop on Algorithms and Data Structures, volume 519 of Lecture Notes in Computer Science, pages 400-411. Springer, 1991.
- [143] R. Morris. Scatter storage techniques. Communications of the ACM, 11(1):38– 44, 1968.
- [144] S. S. Muchnick. Advanced Compiler Design and Implementation. Morgan Kaufmann, 1997.
- [145] S. Näher and O. Zlotowski. Design and implementation of efficient data types for static graphs. In 10th European Symposium on Algorithms, volume 2461 of Lecture Notes in Computer Science, pages 748–759. Springer, 2002.
- [146] G. Nemhauser and Z. Ullmann. Discrete dynamic programming and capital allocation. Management Science, 15(9):494-505, 1969.
- [147] G. Nemhauser and L. Wolsey. Integer and Combinatorial Optimization. Wiley, 1988.

- [148] J. Nešetřil, H. Milková, and H. Nešetřilová. Otakar Boruvka on minimum spanning tree problem: Translation of both the 1926 papers, comments, history. *Discrete Mathematics*, 233(1–3):3–36, 2001.
- [149] K. S. Neubert. The flashsort1 algorithm. *Dr. Dobb's Journal*, pages 123–125, February 1998.
- [150] J. Nievergelt and E. Reingold. Binary search trees of bounded balance. *SIAM Journal of Computing*, 2:33–43, 1973.
- [151] K. Noshita. A theorem on the expected complexity of Dijkstra's shortest path algorithm. *Journal of Algorithms*, 6(3):400–408, 1985.
- [152] R. Pagh and F. Rodler. Cuckoo hashing. *Journal of Algorithms*, 51:122–144, 2004.
- [153] W. W. Peterson. Addressing for random access storage. *IBM Journal of Research and Development*, 1(2), Apr. 1957.
- [154] S. Pettie. Towards a final analysis of pairing heaps. In 46th IEEE Symposium on Foundations of Computer Science, pages 174–183, 2005.
- [155] S. Pettie and V. Ramachandran. An optimal minimum spanning tree algorithm. In 27th International Colloquium on Automata, Languages and Programming, volume 1853 of Lecture Notes in Computer Science, pages 49–60. Springer, 2000.
- [156] J. Pinkerton. Voyages and Travels, volume 2. 1808.
- [157] P. J. Plauger, A. A. Stepanov, M. Lee, and D. R. Musser. *The C++ Standard Template Library*. Prentice Hall, 2000.
- [158] R. C. Prim. Shortest connection networks and some generalizations. *Bell Systems Technical Journal*, pages 1389–1401, Nov. 1957.
- [159] W. Pugh. Skip lists: A probabilistic alternative to balanced trees. *Communications of the ACM*, 33(6):668–676, 1990.
- [160] A. Ranade, S. Kothari, and R. Udupa. Register efficient mergesorting. In *High Performance Computing*, volume 1970 of Lecture Notes in Computer Science, pages 96–103. Springer, 2000.
- [161] J. H. Reif. Depth-first search is inherently sequential. *Information Processing Letters*, 20(5):229–234, 1985.
- [162] N. Robertson, D. P. Sanders, P. Seymour, and R. Thomas. Efficiently four-coloring planar graphs. In 28th ACM Symposium on Theory of Computing, pages 571–575, 1996.
- [163] G. Robins and A. Zelikwosky. Improved Steiner tree approximation in graphs. In 11th ACM-SIAM Symposium on Discrete Algorithms, pages 770–779, 2000.
- [164] P. Sanders. Fast priority queues for cached memory. ACM Journal of Experimental Algorithmics, 5(7), 2000.
- [165] P. Sanders and D. Schultes. Highway hierarchies hasten exact shortest path queries. In *13th European Symposium on Algorithms*, volume *36*69 of Lecture Notes in Computer Science, pages 568–579. Springer, 2003.
- [166] P. Sanders and D. Schultes. Engineering fast route planning algorithms. In 6th Workshop on Experimental Algorithms, volume 4525 of Lecture Notes in Computer Science, pages 23–36. Springer, 2007.

- [167] P. Sanders and S. Winkel. Super scalar sample sort. In 12th European Symposium on Algorithms, volume 3221 of Lecture Notes in Computer Science, pages 784–796. Springer, 2004.
- [168] R. Santos and F. Seidel. A better upper bound on the number of triangulations of a planar point set. *Journal of Combinatorial Theory, Series A*, 102(1):186–193, 2003
- [169] R. Schaffer and R. Sedgewick. The analysis of heapsort. *Journal of Algo- rithms*, 15:76–100, 1993.
- [170] A. Schönhage. Storage modification machines. SIAM Journal on Computing, 9:490-508, 1980.
- [171] A. Schönhage and V. Strassen. Schnelle Multiplikation großer Zahlen. *Computing*, 7:281–292, 1971.
- [172] A. Schrijver. Theory of Linear and Integer Programming. Wiley, 1986.
- [173] D. Schultes. Route Planning in Road Networks. PhD thesis, 2008.
- [174] R. Sedgewick. Analysis of shellsort and related algorithms. In *4th European Symposium on Algorithms*, volume 1136 of Lecture Notes in Computer Science, pages 1–11. Springer, 1996.
- [175] R. Sedgewick and R. Flajolet. An Introduction to the Analysis of Algorithms. Addison-Wesley, 1996.
- [176] R. Seidel and C. Aragon. Randomized search trees. *Algorithmica*, 16(4–5):464–497, 1996.
- [177] R. Seidel and M. Sharir. Top-down analysis of path compression. *SIAM Journal of Computing*, 34(3):515–525, 2005.
- [178] M. Sharir. A strong-connectivity algorithm and its applications in data flow analysis. *Computers and Mathematics with Applications*, 7(1):67–72, 1981.
- [179] J. C. Shepherdson and H. E. Sturgis. Computability of recursive functions. *Journal of the ACM*, 10(2):217–255, 1963.
- [180] J. Singler, P. Sanders, and F. Putze. MCSTL: The Multi-Core Standard Template Library. In *Euro-Par*, volume 4641 of Lecture Notes in Computer Science, pages 682–694. Springer, 2007.
- [181] M. Sipser. *Introduction to the Theory of Computation* MIT Press, 1998.
- [182] D. D. Sleator and R. E. Tarjan. A data structure for dynamic trees. *Journal of Computer and System Sciences*, 26(3):362–391, 1983.
- [183] D. D. Sleator and R. E. Tarjan. Self-adjusting binary search trees. *Journal of the ACM*, 32(3):652–686, 1985.
- [184] D. Spielman and S.-H. Teng. Smoothed analysis of algorithms: Why the simplex algorithm usually takes polynomial time. *Journal of the ACM*, 51(3):385–463, 2004.
- [185] R. E. Tarjan. Depth first search and linear graph algorithms. *SIAM Journal on Computing*, 1:146–160, 1972.
- [186] R. E. Tarjan. Efficiency of a good but not linear set union algorithm. *Journal of the ACM*, 22(2):215–225, 1975.
- [187] R. E. Tarjan. Shortest paths. Technical report, AT&T Bell Laboratories, 1981.
- [188] R. E. Tarjan. Amortized computational complexity. *SIAM Journal on Algebraic and Discrete Methods*, 6(2):306–318, 1985.

- [189] R. E. Tarjan and U. Vishkin. An efficient parallel biconnectivity algorithm. *SIAM Journal on Computing*, 14(4):862–874, 1985.
- [190] M. Thorup. Undirected single source shortest paths in linear time. *Journal of the ACM*, 46:362–394, 1999.
- [191] M. Thorup. Even strongly universal hashing is pretty fast. In 11th Annual ACM-SIAM Symposium on Discrete Algorithms, pages 496–497, 2000.
- [192] M. Thorup. Compact oracles for reachability and approximate distances in planar digraphs. *Journal of the ACM*, 51(6):993–1024, 2004.
- [193] M. Thorup. Integer priority queues with decrease key in constant time and the single source shortest paths problem. In 35th ACM Symposium on Theory of Computing, pages 149–138, 2004.
- [194] M. Thorup. Integer priority queues with decrease key in constant time and the single source shortest paths problem. *Journal of Computer and System Sciences*, 69(3):330–353, 2004.
- [195] M. Thorup and U. Zwick. Approximate distance oracles. In *33rd ACM Symposium on the Theory of Computing*, pages 183–192, 2001.
- [196] A. Toom. The complexity of a scheme of functional elements realizing the multiplication of integers. *Soviet Mathematics Doklady*, 150(3):496–498, 1963.
- [197] Unknown. Der Handungsreisende wie er sein soll und was er zu thun hat, um Auftraege zu erhalten und eines gluecklichen Erfolgs in seinen Geschaeften gewiss zu sein Von einem alten Commis-Voyageur. 1832.
- [198] P. van Emde Boas. Preserving order in a forest in less than logarithmic time. *Information Processing Letters*, 6(3):80–82, 1977.
- [199] R. Vanderbei. *Linear Programming: Foundations and Extensions*. Springer, 2001.
- [200] V. Vazirani. Approximation Algorithms. Springer, 2000.
- [201] J. von Neumann. First draft of a report on the EDVAC. Technical report, University of Pennsylvania, 1945.
- [202] J. Vuillemin. A data structure for manipulating priority queues. *Communications of the ACM*, 21:309–314, 1978.
- [203] L. Wall, T. Christiansen, and J. Orwant. *Programming Perl*. O'Reilly, 3rd edition, 2000.
- [204] I. Wegener. BOTTOM-UP-HEAPSORT, a new variant of HEAPSORT beating, on an average, QUICKSORT (if *n* is not very small). *Theoretical Computer Science*, 118(1):81–98, 1993.
- [205] I. Wegener. Complexity Theory: Exploring the Limits of Efficient Algorithms. Springer, 2005.
- [206] R. Wickremesinghe, L. Arge, J. S. Chase, and J. S. Vitter. Efficient sorting using registers and caches. *ACM Journal of Experimental Algorithmics*, 7(9), 2002.
- [207] R. Wilhelm and D. Maurer. Compiler Design. Addison-Wesley, 1995.
- [208] J. W. J. Williams. Algorithm 232: Heapsort. *Communications of the ACM*, 7:347–348, 1964.



## Index

"folklore" (result), 79 15-puzzle, 248	approximation algorithm, 241 average case, <b>41</b> , 84, 103, 107, 109, 115,
	117, 124, 148, 199, 205, 245
Aarts, E. H. L., 255	global, 41
(a,b)-tree, see under sorted sequence	master theorem, <b>37</b> , 104
Abello, J., 232	randomized, <b>45</b> , 107, 109, 115, 121
Ackermann, W., 224	recursion, 9, 16, 37, 104
Ackermann function (inverse), 224	recursive, 9, 12
addition, 2	smoothed analysis, 262
address, 24, 27	sum, 4, <b>36</b>
Adel'son-Vel'skii, G. M., 165	worst case, 109
adjacency array, see under graph	algorithm design, 1
adjacency list, see under graph	"make the common case fast", 66
adjacency matrix, see under graph	algebraic, 9, 86, 87, 89, 101, 171, 174
adjacent, 49	black-box solvers, 234, 248, 261
Aggarwal, A., 120	ce <mark>rtif</mark> icate, <b>33</b> , 36, 5 <mark>1</mark> , 187
Aho, A. V., 165	de <mark>te</mark> rministic, <b>46</b> , <mark>10</mark> 0
Ahuja, R. K., 201	divide-and-conquer, 7, 34, 37, 103
al-Khwarizmi, Muhammad ibn Musa, 1, 6	building a heap, 131
ALD, see under shortest path	mergesort, 103
algorithm, 1	MSD radix sort, 117
algorithm analysis, 36, see also	multiplication, 7
running time, 36	multiway mergesort, 119
amortized, 60, 135, 158, 203	quicksort, 108, 114
accounting method, 68	dynamic programming, <b>243</b> , <mark>261</mark>
binary counter, 70	Bellman–Ford algorithm, 206
deamortization, 70	changing money, 245
general definition, 71	knapsack, 243, 245
operation sequence, 71	matrix products, chained, 245
potential method, 68	minimum edit distance, 245
token, <b>68</b>	principle of optimality, 243, 246
unbounded array, 66	shortest paths, 193
universality of potential method, 73	evolutionary algorithm, <b>259</b> , 262

greedy, 101, <b>239</b> , 257, 261	Aragon, S. R., 165
changing money, 245	arbitrage, 207
cycle detection, 51	Arge, L., 123
Dijkstra's algorithm, 196	arithmetic, 26
Jarník–Prim algorithm, 219	arithmetics, 24
knapsack, 239, 240	array, 26, <b>26</b> , 59
Kruskal's algorithm, 221	access [·], <b>66</b>
machine scheduling, 241	associative, 81
local search, <b>249</b> , 262	find, <b>82</b>
hill climbing, 250	forall, <b>82</b>
relaxing constraints, 256	insert, <b>82</b>
restarts, 259	remove, <b>82</b>
simplex algorithm, 250	circular, <b>75</b> , 201
simulated annealing, 252	growing, 66
tabu search, 258	popBack, 66
threshold acceptance, 258	pushBack, 66
lookup table, 203	reallocate, 66
preprocessing, 34, 100	shrinking, 66
random sampling, 120, 232	size, <b>66</b>
randomized, <b>45</b> , 92, 125, 1 <mark>65, 226</mark> , 262	sorting, 111
Las Vegas, <b>48</b> , 85, 108, 114	unbounded, 170
Monte Carlo, <b>48</b> , 101	assertion, 32
recursion, 7, 9, 53, 104, 108, 113, 114,	assignment, 28
117, 131, 178, 246	asymptotic, 11, 20, <b>21</b> , 25
result checking, 6, <b>33</b> , 101, 198 systematic search, <b>246</b> , 248, 261	Ausiello, G., 54
constraint programming, 248, <b>262</b>	average case, see under running time
ILP solving, 248	AVL tree, <i>see under</i> sorted sequence
iterative deepening, 248	AWK, 81
knapsack, 246	
use of sorting, 34, 99–101, 125, 172, 239	B (block size), 25
algorithm engineering, <b>1</b> , 5, 10, 11, 92, 95,	B-tree, 163
111, 120, 123, 125, 163, 199, 209,	bandwidth, 25
257, 261	base,
alignment, 8, 163	Bast, H., 212
all-pairs shortest path, see under	Bayer, R., 163
shortest path	Beier, R., 245
allocate, 27	Bellman, R., 206
Alon, N., 97	Bellman-Ford algorithm, see under
amortized, see under algorithm analysis	shortest path
analysis, see also algorithm analysis	Bender, M. A., 165
ancestor, 52	Bentley, J. L., 124
AND, <b>24</b>	Bertsekas, D. P., 262
Andersson, A, 125	best case, see under running time
antisymmetric, <b>264</b>	best-first branch-and-bound, 128
Applegate, D. L., 230	bin packing, 146, 242
approximation algorithm, 217, <b>240</b>	binary heap, see under priority queue
approximation ratio, 240	binary operation, 24
Aragon, C. R., 257	binary search, <i>see under</i> searching
<del>-</del>	

binary search tree, see under	Cayley, A., 174
sorted sequence	census, 99
binomial coefficient, 270	certificate, see algorithm design
binomial heap, see under priority queue	certifying algorithm, 33
binomial tree, 137	changing money, 245
bisection method, 35	characteristic function, 54
bit operation, 24	Chase, S., 123
Bixby, E. E., 230	Chazelle, B., 166, 232
Blelloch, G. E., 125	checksum, 6
block, <i>see</i> memory block	Cheriyan, J., 189
Blum, N., 124, 165	Cherkassky, B., 214
Boolean formula, 242	Chernoff bound, 122, 269
Boolean value, <b>26</b>	chess, 81
Boost, 57	child, 52
Bellman–Ford algorithm, 214	Chvátal, V., 230
Dijkstra's algorithm, 214	class, 26, 27, <b>31</b>
graph, 173	clique, see under graph
graph traversal, 189	clock cycle, 25
union–find, 231	clustering, 217
Boruvka, O., 231	Coffman, E. G., 146
Botelho, F., 97	Cohen-Or, D., 174
bottleneck shortest path, 217	collision, 82
bottom-up heap operation, 131	combinatorial search, 81
bounded array, 59	comparison, 24
branch, 24	three-way, 34, 108, 109
branch prediction, 125, 162	two-way, 35
branch-and-bound, 128, 246	comparison-b <mark>a</mark> sed algorithm, 34, 106
branch-and-cut, 249	competitive ratio, 242
Bro Miltersen, P., 97	compiler, 3, 26, 58, 81, 123
Brodal, G., 141, 143	symbol table, 81
Brown, M. R., 79	comp <mark>lex number, 31, 1</mark> 00
Brown, R., 143	com <mark>ple</mark> xity, 24, see also running time
Buchsbaum, A., 232	com <mark>pl</mark> exity theory, 5 <mark>4</mark>
bucket, 121	composite data structure, 27
bucket sort, see under sorting	composite type, 26
	computation, model of, 24
C, 26	concave function, 200, 265
C++, 17, 26, 31, 57, 78, 96, 123, 142, 164,	conditional branch instruction, 125
173, 214, 231	conditional statement, 28
cache, 24	cone, 251
limited associativity, 123	congruent, 264
cache-oblivious, 142, 165	constant, 24
calendar queue, see under priority queue	constant factor, 21, 25
call by reference, 29	constraint, 235
call by value, 29	constraint programming, see under
carry, 1, 2	algorithm design, systematic search
Carter, J., 97	contract, 32
cascading cut, 138	convex, 265
casting out nines, 6	convex polytope, 251

Cook, W. J., 18, 230	Dijkstra's algorithm, see under
cooling schedule, 254	shortest path
coprocessor, 25	Dijkstra, E., 196, 219
core, 25	discrete-event simulation, 128
correctness, 31	disk, see hard disk
cost vector, 235	dispose, 27
crossover operation, 260	distributed system, 25
C#, 26	div, 24
cuneiform script, 59	division (integer), 6
cycle, 50	Driscoll, J., 166
Hamiltonian, 50, 54	dynamic programming, see under
simple, <b>50</b>	algorithm design
testing for, <b>51</b>	dynamic tree, 222
testing for, 61	
DAG, see graph, directed, acyclic	edge, <b>49</b>
Dantzig, G. B., 235	associated information, 167
data dependency, 24	backward, 175, 179
data struct. inv., see under invariant	contraction, 189
data structure, VII	cost, <b>50</b>
	cross, 175, 179, 181
data type, see type	crossing, 51
database, 147, 163	forward, 175, 179
database join, 81	parallel, 167, 173
decision problem, 54	reduced cost, 207, see also
declaration, <b>26</b> , 29	node potential
implicit, 29	tree, 175, 179
decrement (), <b>28</b>	weight, <b>50,</b> 167
degree, 49	edge contraction, 226
Delaunay triangulation, 232	edge query, 168, 171
Demaine, E. D., 165	edgeArray, 168
Dementiev, R., 124, 125, 166, 225	efficiency, see running time
deque, <b>75</b> , 79	Eiffe <mark>l, 5</mark> 6
first, <b>75</b>	eight-queens problem, 248, 256
last, <b>75</b>	element, <b>26</b> , 99
popBack, <b>75</b>	empty sequence $\langle \rangle$ , 27
pushFront, <b>75</b>	equals (=), <b>24</b>
pushBack, <b>75</b>	equivalence relation, 265
pushFront, <b>75</b>	Eratosthenes, 31
dereference, 27	event, <b>266</b>
descendant, 52	evolutionary algorithm, see under
design by contract, 32	algorithm design
deterministic algorithm, see under	exchange argument, 219, 239
algorithm design	exclusive OR (⊕), 24
Devroye, L., 148	execution time, see running time
dictionary, 81, 99	existence problem, 233
diet problem, 235	expected value, 41, 266
Dietzfelbinger, M., 97	exponential search, 35
digit, 1	external memory, see also machine model
digraph, see graph, directed	building heap, 132
<del>-</del> -	= -

1 1 1 100	
lower bound, 120	generic methods, 233
merging, 119	generic programming, <b>31</b> , 173
MST, 225	genome, 259
parallel disks, 120, 125	geometric series, see under sum
priority queue, 139	geometry, 252
queue, 76	GMP, 17
scanning, 119	Goldberg, A., 205, 212, 214
semiexternal algorithm, 226	Goodrich, M. T., 174
sorting, 118, 120, 124	Graefe, G., 163
stack, 76	Graham, R. L., 40, 58, 241
	graph, 49
Fakcharoenphol, J., 215	2-edge-connected components, 187
false, 24	adjacency array, 168
Farach-Colton, M., 165	adjacency list, 170
fast memory, 25	adjacency matrix, 171
ferry connections, 217	undirected, 171
Fibonacci, L., 135	average degree, 228
Fibonacci heap, see under priority queue	BFS, <b>176</b> , 192
field (algebraic), 86, 265	implementation, 188
field (of variable), 27	biconnected components, 188, 189
FIFO queue, <b>74</b> , 177	bidirected, <b>49</b> , 167, 170
external-memory, 76	bipartite, <b>34</b> , 174
first, <b>74</b>	breadth-first search, see BFS
popFront, <b>74</b>	Cayley, 174
pushBack, <b>74</b>	citation network, 167
using circular array, 75	clique, <b>54</b> , 55
using two stacks, 75	coloring, 3 <mark>4, 54</mark> , 55, 255, 257
file, 27	fixed-K annealing, 258
filing card, 145	Kempe chain annealing, 255
Flajolet, P., 40	penalty function annealing, 256
Fleischer, R., 142	XRLF greedy algorithm, 257
floating-point, <b>24</b> , 56, 203	co <mark>m</mark> munication network, 175
flow, 237	co <mark>m</mark> plete, 54
Floyd, R. W., 58, 124	component, 50
for, <b>28</b>	compression, 174
Ford, L. R., Jr., 206	connected components, 50, 177
forest, 51	construction, 168
Fredkin, E., 166	conversion, 168, 169
Fredman, M. L., 97, 135, 143	counting paths, 171
frequency allocation, 258	cut, 172, 218
Frigo, M., 142	cycle detection, 170
function object, 96	DAG, see graph, directed, acyclic (DAG)
function pointer, 123	dense, 171
Funke, S., 212	depth-first search, see DFS
	DFS, 175, <b>178</b> , 206
Gabow, H., 189	backtrack, 178
Gärtner, B., 262	init, 178
garbage collection, <b>57</b>	root, 178
Garey, M. R., 54, 146	traverseNonTreeEdge, 178

traverseTreeEdge, 178 strongly connected components, 50, 175, diameter, 209 181 closed, 183 directed, 49 acyclic (DAG), 50, 51, 52, 180 implementation, 188 invariant, 182 dynamic, 168, 170 more algorithms, 189 ear decomposition, 189 open, 183 edge, see under edge subgraph (induced), 50 edge sequence, 168, 221 topological sorting, 180, 195 exploration, see graph traversal transitive closure, 177 face, 174 traversal, 175 grid, 172 triconnected components, 189 hypergraph, 174 undirected, 49 input, 168 vertex, see node interval graph, 17 visitor, 189 interval-, 100 graphics processor, 25 Kempe chain, 255 greater than (>), 24 layer, 176 greedy algorithm, see under algorithm linked edge objects, 170 design minimum spanning tree, Grossi, R., 166 MST group, 174 MST, see MST grouping, 100 multigraph, 167, 173 growth rate, 20 navigation, 168 Guibas, L. J., 166 negative cycle, see under shortest path network design, 217 Hagerup, T., 125 node, see node half-space, 25 output, 168 Halperin, S., 232 planar, 51, 174 Hamilton, W. R., 50 4-coloring, 255 Han, Y., 125, 143 5-coloring, 256 handle, **26**, 60, 128, Handler, G., 215 embedding, 189 testing planarity, 189 hard disk, 25 random, 208, 257 harmonic sum, see under sum random geometric graph, 257 Harrelson, C., 212 representation, 167 hash function, 82 reversal information, 168 hash table, see hashin SCC, see graph, strongly connected hashing, **81**, 100 component closed, 90 shortest path, see shortest path large elements, 96 shrunken graph, 182 large keys, 96 sparse, 170 linear probing, 83, 90 static, 168 cyclic, 91 Steiner tree, 228 find, 90 2-approximation, 228 insert. 90 street network, 51 remove, 90 strongly connected component unbounded, 91 certificate, 187 open, 90 open, 182 perfect, 92

stack, 79 Konheim, A. G., 165 Korf, R. E., 248 TreeMap, 164 Korst, J., 255 TreeSet, 164 vector, 79 Korte, B., 232 JDSL, 57 Kosaraju, S. R., 189 Dijkstra's algorithm, Kothari, S., 123 graph, 174 Kruskal, J., 221 graph traversal, 189 MST, 231 Landis, E. M., 165 PriorityQueue, 147 Larsen, P.-A., 163 Jiang, T., 125 Las Vegas algorithm, see under <mark>14</mark>6, 257 Johnson, D. S., 54 algorithm design, randomized jump, 24 latency, 25 Lawler, E. L., 230 Kaligosi, K., 125 leading term, 22 Kaplan, H., 143 leaf, 52 LEDA, 17, 57 Karatsuba, A., 9 Karger, D., 232 Bellman-Ford algorithm, 214 Karlin, A., 97 bounded stack, 78 Karmakar, N., 237 Dijkstra's algorithm, 214 Karp, R., 230 graph, 173 Katajainen, J., 79, 141 graph traversal, 188 Katriel, I., 232 *h\_array*, 96 Kellerer, H., 233 list, 78 Kempe, A. B., 256 map, 9 Kempe chain, see under graph MST, 231 Kettner, L., 124, 166  $node\_pq, 21$ key, 82, 99, 127 priority queue, 142 queue, 78 Khachian, L., 237 King, V., 232 sortseq, 164 Klein, P., 232 stack. knapsack, 54, 191 static graph, 173 union-find, 231 knapsack problem, 233 2-approximation (round), 240 Lee, L. W., 173 left-to-right maximum, 42, 45, 110, 200 as an ILP, 238 Leiserson, C. E., 125, average case, 245 branch-and-bound algorithm, 246 Lenstra, J. K. less than (<), 24 dynamic programming, 243 Levenshtein distance, 245 by profit, 245 evolutionary algorithm, 260 Levin, D., 174 fractional, 238, 239, 247 lexicographic order, 100, 265 fractional solver, 239 Li, M., 125 greedy algorithm, 240 linear algebra, 171, 252 local search, 250 linear order, 99, 215, **265** simulated annealing, 255 linear program (LP), 234 use of, 233 fractional solution, 238 knot, 59 integer (ILP), 236, 238 Knuth, D., 40, 58, 97, 125 0-1 ILP, 238, 248 Komlos, J., 97 branch-and-cut, 249

knapsack, 238	load instruction, 24
pigeonhole principle, 242	local search, <i>see under</i> algorithm design
set covering, 239	locate, see under sorted sequence
maximum flow, 237	logarithm, 264
minimum-cost flow, 237	logical operations, 24
mixed integer (MILP), 238	loop, <b>28</b> , 36
relaxation of ILP, 238	loop fusion, 3
rounding, 238	loop invariant, see under invariant
shortest path, 236	lower bound, 241
simplex algorithm, 250	"breaking", 116
smoothed analysis, 262	element uniqueness, 108
solver, 262	external sorting, 120
strict inequality, 251	minimum, 107
tight inequality, 251	pairing heap priority queue, 143
linearity of expectations, 41, 85, 86, 110,	sorting, 106
228, <b>267</b>	lower-order term, 22
list, 27, 59, 83, 170	
blocked, 76, 106, 118	LP, see linear program
bulk insert, 105	Lucas, E., 75 Lumsdaine, A., 173
circular, 136, 170	· · · · · · · · · · · · · · · · · · ·
concat, 64, 65	Lustig, I. J., 262
concatenate, 60, 65	
doubly linked, <b>60</b> , 145	M (size of fast memory), 25
dummy item, <b>61</b> , 170	machine instruction, see instruction
empty, 61	machine model, 21, 23
find, 63, 65	accurate, 25
findNext, 64, 65	complex, 25
first, 64, 65	external m <mark>em</mark> ory, 25
head, 64, 65	parallel, <b>24</b> , <b>25</b>
insert, <b>62</b> , 64, 65	RAM, <b>23</b> , 26
interference between ops., 64	real <mark>, 24</mark>
invariant, 60	se <mark>que</mark> ntial, 23
isEmpty, 64, 65	si <mark>m</mark> ple, 25
last, 64, 65	von Neumann, 23
linked, 60	word, 125
makeEmpty, 64, 65	machine program, 24, 26
memory management, 61, 64	machine scheduling, 241
move item, <b>61</b>	decreasing-size algorithm, 242
popBack, 64	online algorithm, 241
popFront, 64, 65	shortest-queue algorithm, <b>241</b>
pushBack, 64, 65	machine word, 23, 24
pushFront, 64, 65	Maggs, B. M., 125
remove, 61, 64, 65	makespan, 241
rotation, 64	map coloring, 255
singly linked, 65, 95	Markov, A., 48
size, <b>64</b>	Markov's inequality, see under
sorting, 105	inequality
splice, <b>61</b> , 65	Martello, S., 233
swapping sublists, <b>64</b>	Martinez, C., 124

master theorem, see under algorithm	MST, <b>217</b>
analysis 👠	2-approximation of TSP, 230
mating, 260	Boruvka's algorithm, 231
Matousek, J., 262	clustering, 217, 232
matrix, 171	cut property, <b>218</b> , 221
matrix products, chained, 245	cycle property, 219, 221, 232
Mauer, D., 58	Euclidean, 232
maximization problem, 233	external memory, 225
maximum flow, 237	Held-Karp lower bound, 230
McCreight, E. M., 163	Jarník-Prim algorithm, 219
McGeoch, L. A., 257	maximum-cost spanning tree, 218
McIlroy, M. D., 124	parallel, 232
median, 114, see also selection, 265	semiexternal Kruskal algorithm, 226
Mehlhorn, K., 79, 97, 165, 166, 189, 201,	streaming algorithm, 222
209, 215, 229	uniqueness conditions, 219
Mehnert, J., 166	use of, 217, 228, 232
member variable, 31	multicore processor, 25
memcpy, 78	multigraph, 167, 173
memory access, 24	multikey quicksort, 113
memory block, 25	multiplication (integer)
memory cell, 23, see also machine word	Karatsuba, 9
memory management, 27	refined, 12
memory size, 24	recursive, 7
Mendelson, R., 143	school method, 1, 3
mergesort, see under sorting	use of, 1
merging, 103, 244	multithreading, 25
external, 119	mutation, 259
multiway, 119	
Meyer auf der Heide, F., 97	Näher, S., 166, 171
Meyer, B., 56	Nemhauser, G., 244, 248
Meyer, U., 189, 205, 214	network, 25, see also graph
Michel, L., 262	co <mark>m</mark> munication net <mark>w</mark> ork, 49
minimization problem, 233	de <mark>s</mark> ign, 217
minimum edit distance, 245	Neubert, K. S., 125
minimum spanning forest, see	Nilsson, S., 125
MST	node, <b>49</b>
minimum spanning tree, see	active, 178
MST	associated info., 167
mobile device, 25	depth, 52, 176
mod, 24	dfsNum, 178
modulo, 7, <b>264</b>	finishing time, 178
Monte Carlo algorithm, see under	interior, 52
algorithm design, randomized	marked, 178
Moret, B., 231	numbering, 167
Morris, R., 97	ordering relation (≺), N79
most significant distinguishing index, 202	potential, <b>207</b> , 211, 230
move-to-front, 44	reached, 176, 197
msd, see most significant distinguishing	representative, 177, 182
index	scanned, 196

NodeArray, 168, 173 Noshita, K., 200 NOT, 24 NP, 53 NP+complete, 54 NP-hard, 55, 238 numeric type, 26	Peterson, W. W., 90 Petrank, E., 97 Pettie, S., 143, 232 Pferschy, U., 233 pigeonhole principle, 242 pipelining, 4 Pisinger, D., 233 pivot, <b>108</b> , 121
$O(\cdot)$ , 21 $o(\cdot)$ , 21 object, 26 object-oriented, 31 objective function, 233 of (in type declaration), 26, 27, 31 Ofman, Y., 9 $\Omega(\cdot)$ , 21 $\omega(\cdot)$ , 21 online algorithm, 44, 241 optimization, 233 optimization problem, 56, 233 OR, 24 Orlin, J., 201 oversampling, 121	selection, 111, 124 Plaxton, C. G., 125 pointer, 26 polynomial, 22, 101, see also under running time polytope, 251 population, 259 postcondition, 32 potential function, see node, potential powers (of numbers), 32 Pratt, V. R., 124 precedence relation, 49 precondition, 32 predecessor, 60, 60 Priebe, V., 209
P, 53 Pagh, R., 97 pair, 27	Prim. R. C., 219 Prim's algorithm, see MST, Jarník–Prim algorithm prime number, 31, 86, 101, <b>265</b>
pairing heap, <i>see under</i> priority queue parallel assignment, 28 parallel processing, 24, <b>25</b> , 121, 214, 232, 259, 262	abundance, 88 primitive operation full adder, 1 product, 2
parameter, <b>29</b> actual, 29 formal, 29	principle of optimality, <b>243</b> , 246 priority queue, <b>127</b> addressable, <b>128</b> , 133, 198
parameterized class, <b>31</b> parent, <b>52</b> Pareto, V., 244	binary heap, 129, 199 addressable, 129, 133 bottom up delete Min, 142
Pareto-optimal, 244, 261 parser, 53 partition, 222	building, 131 bulk insertion, 133 deleteMin, 131
Pascal, 26 Patashnik, O., 40, 58 path, <b>50</b> simple, <b>50</b>	insert, <b>130</b> invariant, 129 siftDown, <b>131</b> siftUp, <b>130</b>
Perl, 81 permutation, 42, 100, 101, 106 random, 42, 45	binomial heap, 137 bounded, 129 bucket, 143
persistent data structure, 166 Peru, 59	bucket queue, <b>201</b> invariant, 202

calendar queue, 143	functional, 105
decrease key, <b>128</b> , 199	logical, 105
deleteMin, <b>127</b>	programming model, see machine model
double-ended, 156	Prokop, H., 142
éxternal, 139	pseudo-polynomial algorithm, 245
fat heap, 143	pseudocode, 26, 56
Fibonacci heap, 135, 199, see also	Puget, JF., 262
priority queue, heap-ordered forest	Pugh, W., 165
decreașeKey, <mark>138</mark>	
deleteM <mark>in, <b>136</b></mark>	quartile, 114, see also selection
item, <b>136</b>	queue, 27, 170, see also FIFO
rank, <b>136</b>	quickselect, see under selection
heap-ordered fo <mark>re</mark> st, <b>133</b>	quicksort, see under sorting
cut, <b>133</b>	quipu, <b>59</b>
decreaseKey, <b>133</b>	
deleteMin, 133	radix sort, see under sorting
insert, 133	Radzik, T., 214
invariant, 133	RAM model, see under machine model
link, <b>133</b>	Ramachandran, S., 142
merge, 135	Ramachandran, V., 232
new tree, 133	Raman, R., 125
remove, 135	Ranade, A., 123
insert, <b>128</b>	random experiment, 266
integer, 142, 143, <b>201</b>	random number, 46
item, 133	random source, 57
memory management, 141	random variable, 41, <b>266</b>
merge, <b>128</b>	independe <mark>nt, 268</mark>
minimum, <b>127</b> , 130, 133	indicator, 266
monotone, 128, 143, 198, <b>201</b>	product, 268
naive, 129, 199	randomized algorithm, see under
pairing heap, 135, see also	algorithm design; algorithm analysis
priority q., heap-ordered forest	rank <mark>, 1</mark> 03, <b>265</b>
complexity, 143	Rao, \$., 215
three-pointer items, 135	realloe, 78
two-pointer items, 135	recombination, 259, 260
radix heap, 201	record, see composite type
base <i>b</i> , 204	recurrence relation, 9, 16, 35, 37, 58
remove, 128	recursion, 29, see also under
thin heap, 143	algorithm design; algorithm
unbounded, 129	analysis
use of, 102, 120, 125, 128, 198, 226	elimination, 113, 141
probability, 266	red-black tree, see under sorted sequence
probability space, 41, <b>266</b>	reduction, 55
problem instance, 20	reflexive, 265
procedure, 29	register, 24, <b>24</b> , 25
profit vector, see cost vector	Reif, J., 189
program, 24	relation, 265
program analysis, <i>see</i> algorithm analysis	antisymmetric, 264
programming language, 26, 28, 58	equivalence, 265

reflexive, 265	range, 100
symmetric, 265	shortest path, see under shortest path
transitive, 265	Sedgewick, R., 40, 125, 142, 143
weakly antisymmetric, 265	Seidel, R., 165, 174, 224
relaxation, 256, see also under	selection, 114
linear program	deterministic, 124
remainder, 24	quickselect, 114
Remez, O., 174	streaming, 115
removing from a sequence, 60	self-loop, 49
repeat, 28	semicolon (in pseudocode), 28
result checking, see under algorithm design	sentinel, 63, 95, 102, 106, 141
return, 29	sequence, 27, 27, 59, 100
Rivest, R. L., 124	overview of operations, 77
road map, 49	space efficiency, 77
Robertson, N., 255	series, see sum
Robins, G., 229	server, 25
Rodeh, M., 165	set, <b>27</b>
root, see under tree	set covering, 239
Roura, S., 124	Seymour, P., 255
run, see under sorting	S <mark>h</mark> apiro, H. D., 231
running time, 20, <b>24</b> , 28, 36, see also	shared memory, 25
algorithm analysis	Sharir, M., 189
average case, <b>20</b> , 41	Shell sort, see under sorting
best case, <b>20</b> , 24	Sheperdson, J., 23
polynomial, 53	shift, 24
worst case, 20	Shmoys, D. B., 230
	shortest path, 191
worst case, <b>20</b> sample space, <b>266</b>	
	shortest path, <b>191</b> acyclic, 1 <b>92</b> ALD (average linear Dijkstra), <b>205</b> , 214
sample space, 266	shortest path, <b>191</b> acyclic, 192 ALD (average linear Dijkstra), <b>205</b> , 214 all-pairs, 191
sample space, <b>266</b> Sanders, D. P., 255 Sanders, P., 124, 125, 141, 142, 166, 212, 214, 215, 225, 232	shortest path, 191 acyclic, 192 ALD (average linear Dijkstra), 205, 214 all-pairs, 191 all-pairs with negative costs, 207
sample space, <b>266</b> Sanders, D. P., 255 Sanders, P., 124, 125, 141, 142, 166, 212,	shortest path, 191 acyclic, 192 ALD (average linear Dijkstra), 205, 214 all-pairs, 191 all-pairs with negative costs, 207 arbitrary edge costs, 206
sample space, <b>266</b> Sanders, D. P., 255 Sanders, P., 124, 125, 141, 142, 166, 212, 214, 215, 225, 232	shortest path, 191 acyclic, 192 ALD (average linear Dijkstra), 205, 214 all-pairs, 191 all-pairs with negative costs, 207 arbitrary edge costs, 206 as a linear prograph, 236
sample space, <b>266</b> Sanders, D. P., 255 Sanders, P., 124, 125, 141, 142, 166, 212, 214, 215, 225, 232 Santos, R., 174 Sarnak, N., 166 SAT solver, 242	shortest path, 191 acyclic, 192 ALD (average linear Dijkstra), 205, 214 all-pairs, 191 all-pairs with negative costs, 207 arbitrary edge costs, 206 as a linear program, 236 A* search, 211
sample space, <b>266</b> Sanders, D. P., 255 Sanders, P., 124, 125, 141, 142, 166, 212, 214, 215, 225, 232 Santos, R., 174 Sarnak, N., 166	shortest path, 191 acyclic, 192 ALD (average linear Dijkstra), 205, 214 all-pairs, 191 all-pairs with negative costs, 207 arbitrary edge costs, 206 as a linear prograph, 236
sample space, <b>266</b> Sanders, D. P., 255 Sanders, P., 124, 125, 141, 142, 166, 212, 214, 215, 225, 232 Santos, R., 174 Sarnak, N., 166 SAT solver, 242 satisfiability problem, <b>54</b> satisfiable, 242	shortest path, 191 acyclic, 192 ALD (average linear Dijkstra), 205, 214 all-pairs, 191 all-pairs with negative costs, 207 arbitrary edge costs, 206 as a linear program, 236 A* search, 211 Bellman-Ford algorithm, 206 refined, 214
sample space, <b>266</b> Sanders, D. P., 255 Sanders, P., 124, 125, 141, 142, 166, 212, 214, 215, 225, 232 Santos, R., 174 Sarnak, N., 166 SAT solver, 242 satisfiability problem, <b>54</b> satisfiable, 242 Schäfer, G., 209	shortest path, 191 acyclic, 192 ALD (average linear Dijkstra), 205, 214 all-pairs, 191 all-pairs with negative costs, 207 arbitrary edge costs, 206 as a linear program, 236 A* search, 211 Bellman-Ford algorithm, 206 refined, 214 bidirectional search, 209
sample space, <b>266</b> Sanders, D. P., 255 Sanders, P., 124, 125, 141, 142, 166, 212, 214, 215, 225, 232 Santos, R., 174 Sarnak, N., 166 SAT solver, 242 satisfiability problem, <b>54</b> satisfiable, 242 Schäfer, G., 209 Schaffer, R., 142	shortest path, 191 acyclic, 192 ALD (average linear Dijkstra), 205, 214 all-pairs, 191 all-pairs with negative costs, 207 arbitrary edge costs, 206 as a linear program, 236 A*-search, 211 Bellman-Ford algorithm, 206 refined, 214 bidirectional search, 209 bottleneck, 217, 232
sample space, <b>266</b> Sanders, D. P., 255 Sanders, P., 124, 125, 141, 142, 166, 212, 214, 215, 225, 232 Santos, R., 174 Sarnak, N., 166 SAT solver, 242 satisfiability problem, <b>54</b> satisfiable, 242 Schäfer, G., 209	shortest path, 191 acyclic, 192 ALD (average linear Dijkstra), 205, 214 all-pairs, 191 all-pairs with negative costs, 207 arbitrary edge costs, 206 as a linear program, 236 A*-learch, 211 Bellman-Ford algorithm, 206 refined, 214 bidirectional search, 209 bottleneck, 217, 232 by table lookup, 212
sample space, <b>266</b> Sanders, D. P., 255 Sanders, P., 124, 125, 141, 142, 166, 212, 214, 215, 225, 232 Santos, R., 174 Sarnak, N., 166 SAT solver, 242 satisfiability problem, <b>54</b> satisfiable, 242 Schäfer, G., 209 Schaffer, R., 142	shortest path, 191 acyclic, 192 ALD (average linear Dijkstra), 205, 214 all-pairs, 191 all-pairs with negative costs, 207 arbitrary edge costs, 206 as a linear program, 236 A*-search, 211 Bellman-Ford algorithm, 206 refined, 214 bidirectional search, 209 bottleneck, 217, 232
sample space, <b>266</b> Sanders, D. P., 255 Sanders, P., 124, 125, 141, 142, 166, 212, 214, 215, 225, 232 Santos, R., 174 Sarnak, N., 166 SAT solver, 242 satisfiability problem, <b>54</b> satisfiable, 242 Schäfer, G., 209 Schaffer, R., 142 scheduling, 128, 191, <b>241</b> Schevon, C., 257 Schönhage, A., 18	shortest path, 191 acyclic, 192 ALD (average linear Dijkstra), 205, 214 all-pairs, 191 all-pairs with negative costs, 207 arbitrary edge costs, 206 as a linear program, 236 A*-learch, 211 Bellman-Ford algorithm, 206 refined, 214 bidirectional search, 209 bottleneck, 217, 232 by table lookup, 212
sample space, <b>266</b> Sanders, D. P., 255 Sanders, P., 124, 125, 141, 142, 166, 212, 214, 215, 225, 232 Santos, R., 174 Sarnak, N., 166 SAT solver, 242 satisfiability problem, <b>54</b> satisfiable, 242 Schäfer, G., 209 Schaffer, R., 142 scheduling, 128, 191, <b>241</b> Schevon, C., 257 Schönhage, A., 18 Schrijver, A., 262	shortest path, 191 acyclic, 192 ALD (average linear Dijkstra), 205, 214 all-pairs, 191 all-pairs with negative costs, 207 arbitrary edge costs, 206 as a linear program, 236 A*-search, 211 Bellman-Ford algorithm, 206 refined, 214 bidirectional search, 209 bottleneck, 217, 232, by table lookup, 212 constrained, 215, 246 correctness criterion, 194 DAG, 195
sample space, <b>266</b> Sanders, D. P., 255 Sanders, P., 124, 125, 141, 142, 166, 212, 214, 215, 225, 232 Santos, R., 174 Sarnak, N., 166 SAT solver, 242 satisfiability problem, <b>54</b> satisfiable, 242 Schäfer, G., 209 Schaffer, R., 142 scheduling, 128, 191, <b>241</b> Schevon, C., 257 Schönhage, A., 18 Schrijver, A., 262 Schultes, D., 212, 225	shortest path, 191 acyclic, 192 ALD (average linear Dijkstra), 205, 214 all-pairs, 191 all-pairs with negative costs, 207 arbitrary edge costs, 206 as a linear progrant, 236 A* search, 211 Bellman-Ford algorithm, 206 refined, 214 bidirectional search, 209 bottleneck, 217, 232 by table lookup, 212 constrained, 215, 246 correctness criterion, 194 DAG, 195 Dijkstra's algorithm, 196
sample space, <b>266</b> Sanders, D. P., 255 Sanders, P., 124, 125, 141, 142, 166, 212, 214, 215, 225, 232 Santos, R., 174 Sarnak, N., 166 SAT solver, 242 satisfiability problem, <b>54</b> satisfiable, 242 Schäfer, G., 209 Schaffer, R., 142 scheduling, 128, 191, <b>241</b> Schevon, C., 257 Schönhage, A., 18 Schrijver, A., 262 Schultes, D., 212, 225 search tree, <i>see</i> sorted sequence	shortest path, 191 acyclic, 192 ALD (average linear Dijkstra), 205, 214 all-pairs, 191 all-pairs with negative costs, 207 arbitrary edge costs, 206 as a linear program, 236 A* search, 211 Bellman-Ford algorithm, 206 refined, 214 bidirectional search, 209 bottleneck, 217, 232 by table lookup, 212 constrained, 215, 246 correctness criterion, 194 DAG, 195 Dijkstra's algorithm, 196 invariant, 201
sample space, 266 Sanders, D. P., 255 Sanders, P., 124, 125, 141, 142, 166, 212, 214, 215, 225, 232 Santos, R., 174 Sarnak, N., 166 SAT solver, 242 satisfiability problem, 54 satisfiable, 242 Schäfer, G., 209 Schaffer, R., 142 scheduling, 128, 191, 241 Schevon, C., 257 Schönhage, A., 18 Schrijver, A., 262 Schultes, D., 212, 225 search tree, see sorted sequence searching, 145, see also sorted sequence	shortest path, 191 acyclic, 192 ALD (average linear Dijkstra), 205, 214 all-pairs, 191 all-pairs with negative costs, 207 arbitrary edge costs, 206 as a linear program, 236 A* search, 211 Bellman-Ford algorithm, 206 refined, 214 bidirectional search, 209 bottleneck, 217, 232 by table lookup, 212 constrained, 215, 246 correctness criterion, 194 DAG, 195 Dijkstra's algorithm, 196 invariant, 201 edge relaxation, 194
sample space, 266 Sanders, D. P., 255 Sanders, P., 124, 125, 141, 142, 166, 212, 214, 215, 225, 232 Santos, R., 174 Sarnak, N., 166 SAT solver, 242 satisfiability problem, 54 satisfiable, 242 Schäfer, G., 209 Schaffer, R., 142 scheduling, 128, 191, 241 Schevon, C., 257 Schönhage, A., 18 Schrijver, A., 262 Schultes, D., 212, 225 search tree, see sorted sequence searching, 145, see also sorted sequence binary search, 34, 56, 100, 121, 151	shortest path, 191 acyclic, 192 ALD (average linear Dijkstra), 205, 214 all-pairs, 191 all-pairs with negative costs, 207 arbitrary edge costs, 206 as a linear program, 236 A* tearch, 211 Bellman-Ford algorithm, 206 refined, 214 bidirectional search, 209 bottleneck, 217, 232 by table lookup, 212 constrained, 215, 246 correctness criterion, 194 DAG, 195 Dijkstra's algorithm, 196 invariant, 201 edge relaxation, 194 geometric, 215
sample space, 266 Sanders, D. P., 255 Sanders, P., 124, 125, 141, 142, 166, 212, 214, 215, 225, 232 Santos, R., 174 Sarnak, N., 166 SAT solver, 242 satisfiability problem, 54 satisfiable, 242 Schäfer, G., 209 Schaffer, R., 142 scheduling, 128, 191, 241 Schevon, C., 257 Schönhage, A., 18 Schrijver, A., 262 Schultes, D., 212, 225 search tree, see sorted sequence searching, 145, see also sorted sequence binary search, 34, 56, 100, 121, 151 dynamic, 43	shortest path, 191 acyclic, 192 ALD (average linear Dijkstra), 205, 214 all-pairs, 191 all-pairs with negative costs, 207 arbitrary edge costs, 206 as a linear program, 236 A* tearch, 211 Bellman-Ford algorithm, 206 refined, 214 bidirectional search, 209 bottleneck, 217, 232 by table lookup, 212 constrained, 215, 246 correctness criterion, 194 DAG, 195 Dijkstra's algorithm, 196 invariant, 201 edge relaxation, 194 geometric, 215 goal-directed search, 211
sample space, 266 Sanders, D. P., 255 Sanders, P., 124, 125, 141, 142, 166, 212, 214, 215, 225, 232 Santos, R., 174 Sarnak, N., 166 SAT solver, 242 satisfiability problem, 54 satisfiable, 242 Schäfer, G., 209 Schaffer, R., 142 scheduling, 128, 191, 241 Schevon, C., 257 Schönhage, A., 18 Schrijver, A., 262 Schultes, D., 212, 225 search tree, see sorted sequence searching, 145, see also sorted sequence binary search, 34, 56, 100, 121, 151 dynamic, 43 exponential, 35, 56	shortest path, 191 acyclic, 192 ALD (average linear Dijkstra), 205, 214 all-pairs, 191 all-pairs with negative costs, 207 arbitrary edge costs, 206 as a linear program, 236 A* tearch, 211 Bellman–Ford algorithm, 206 refined, 214 bidirectional search, 209 bottleneck, 217, 232 by table lookup, 212 constrained, 215, 246 correctness criterion, 194 DAG, 195 Dijkstra's algorithm, 196 invariant, 201 edge relaxation, 194 geometric, 215 goal-directed search, 211 hierarchical search, 212
sample space, 266 Sanders, D. P., 255 Sanders, P., 124, 125, 141, 142, 166, 212, 214, 215, 225, 232 Santos, R., 174 Sarnak, N., 166 SAT solver, 242 satisfiability problem, 54 satisfiable, 242 Schäfer, G., 209 Schaffer, R., 142 scheduling, 128, 191, 241 Schevon, C., 257 Schönhage, A., 18 Schrijver, A., 262 Schultes, D., 212, 225 search tree, see sorted sequence searching, 145, see also sorted sequence binary search, 34, 56, 100, 121, 151 dynamic, 43	shortest path, 191 acyclic, 192 ALD (average linear Dijkstra), 205, 214 all-pairs, 191 all-pairs with negative costs, 207 arbitrary edge costs, 206 as a linear program, 236 A* tearch, 211 Bellman-Ford algorithm, 206 refined, 214 bidirectional search, 209 bottleneck, 217, 232 by table lookup, 212 constrained, 215, 246 correctness criterion, 194 DAG, 195 Dijkstra's algorithm, 196 invariant, 201 edge relaxation, 194 geometric, 215 goal-directed search, 211

linear average time, 205 insert, 151 multicriteria, 215 invariant, 149 negative cycle, 192 item, 150 nonnegative edge cost, 192 locate, 150 parallel, 214 parent pointer, 161 parent pointer, 193 reduction, 161 public transportation, 19 remove, 153 query, 209 removing a range, 158 relaxing of edges, 194 splitter, 149 single-source, 191 splitting, 157 subpath, 193 adaptable, 165 tentative distance, 194 AVL tree, 165 transit node routing, 212 binary search tree, 147 degenerate, 148 tree, 193 uniqueness, 193 expected height, 148 unit edge cost, 192 implicit, 149 use of, 191, 207 insert, 147 shortest-queue algorithm, locate, 147 perfect balance, 147 shrunken graph, 182 rotation, 149 Sibeyn, J., 225 sibling, 52 selection, 161 sibling pointer, 136 cache-oblivious, 165 Siek, J. G., 173 finger search, 161 sieve of Eratosthenes, 31 first, **146**, 156 SIMD, 25, 95 nsert, 145 simplex algorithm, see under integer, 166 linear programming last, **146**, 1<mark>5</mark>6 locate, 145, 146 simulated annealing, see under merging, 161 algorithm design, local search Singler, J., 124 navigation, 14 Sipser, M., 54 persistent, 166 pr<mark>ed</mark>, **146** Sivadasan, N., 209 Sleator, D., 79, 143, 165, 166, 222 randomized search tree, 165 range searching, 156 slow memory, 25 red-black tree, 155, 164 Smith, S. J., 125 snow plow heuristic, 125 remove, 145 solution skip list, 165 feasible, 233 sparse table, 165 potential, 233 splay tree, 165 sorted sequence, 34, 145 strings, 166 succ, 146 (a,b)-tree, **149** split (node), 152 trie, 166 use of, 146, 147 amortized update cost, 158 weight-balanced tree, 160, 165 augmentation, 160 balance, 153 sorting, 99 build/rebuild, 156 almost sorted inputs, 103 concatenation, 157 bottom-up heapsort, 142 fusing, 153 bucket, 116 height, 150 comparison-based, 116

dynamic, 102	hash_multiset, 96
external, 118	hash_set, 96
flash, 125	iterator, 78, 123
heapsort, 128, 132	list, 78
in-place, <b>101</b> , 111	map, 164
insertion, 36, <b>102</b> , 105	multimap, 164
large elements, 123	multiset, 164
list, 105	priority_queue, 142
lower bound, 116	set, 164
mechanical, 99	sort, 123
mergesort, <b>103</b> , 124	stack, 78
multiway merge, 119	store instruction, 24
numbers, 116, <b>116</b> , 122, 170	Strassen, V., 18
parallel, 121, 125	streaming algorithm, 115, 222
parallel disks, 125	string, 27, 59, 100
quicksort, <b>108</b> , 123, <b>1</b> 24, 148	striping, 125
radix, <b>116</b>	struct, see composite type
LSD, 116	Sturgis, H., 23
MSD, <b>117</b> , 123	STXXL, 124, 141, 142
random numbers, 117	subroutine, 29
run formation, 119, 125	successor, 60, 60
sample, <b>120</b> , 125	succinct data structure, 97
selection, <b>101</b> , 128	Sudoku, 255
Shell sort, 125	sum, 58, see also under algorithm analysis
small inputs, 102, 108	estimation by integral, 271
small subproblems, 111	geometric, 38, <b>270</b>
stable algorithm, <b>116</b>	harmonic, 43, 45, 88, 110, 200, 228, 264,
strings, 113, 116	270
use of, 34, 99–101, 125, 172, 226, 239	Sumerian, 59
word model, 125	survival of the fittest, 259
source node, 49	swap, 28
spellchecking, 125	swee <mark>p-</mark> line algorithm, <mark>1</mark> 46
Spielmann, D., 262	symmetric, <b>265</b>
splitter, 121, 147	syntax, 26
stack, 27, 29, 74, 75	Szemeredi, E., 97
bounded, 75	
external-memory, 76	table, 59
pop, <b>74</b>	tablet, 59
push, <b>74</b>	tabu list, see tabu search
top, <b>74</b>	tabu search, <i>see under</i> algorithm design,
unbounded, 75	local search
statement, 28	tail bound, 269
static array, 27, 59	tail recursion, see recursion, elimination
statistics, 114	Tamassia, R., 174
Stirling's approximation, 107, 118, 270	Tardos, E., 97
STL, 13, 57, 164	target node, 49
deque, 78	Tarjan, R. E., 79, 97, 124, 135, 143, 165,
hash_map, 96	166, 189, 201, 214, 222, 224, 232
hash_multimap, 96	telephone book, 99

template programming, 31, 123	Ullmann, Z., 244
Teng, S. H., 262	unary operation, 24
termination, 33, 34	unbounded array, 60, 66
$\Theta(\cdot)$ , 21	undefined value ( $\perp$ ), <b>26</b>
Thômas, R., 255	uniform memory, 23
Thompson, K., 246	union-find, 222
Thorup, M., 95, 125, 143, 214	path compression, 223
thread, 25	union by rank, 223
threshold acceptance, see under	universe $(\mathcal{U})$ , 233
algorit <mark>hm design, l</mark> ocal <mark>se</mark> arch	upper bound, see worst case
time, see running time	
time step, 24	Vöcking, B., 245
Toom, A., 18	van Emde Boas layout, 165
total order, 99, 265, <b>265</b>	van Emde Boas, P., 166
Toth, P., 233	Van Hentenryck, P., 262
tournament tree, 125	Vanderbei, R. J., 262
Tower of Hanoi, 75	variable, <b>26</b> , 235
Träff, J. L., 232	Vazirani, V., 232
transitive, 265	vector (in C++), 78
translation, 27–30	verification, 32, 103
traveling salesman problem, <b>54</b> , <b>5</b> 5, 56, <b>230</b>	vertex, see node
2-exchange, 250	Vishkin, U., 189
3-exchange, 250	visitor, see under graph
Held-Karp lower bound, 230	Vitányi, P., 125
hill climbing, 250	Vitter, J. S., 120, 123
tree, <b>51</b> , 147	von Neumann, J., 23
depth, 52	von Neumann machine, see under
dynamic, 222	machine model
expression tree, 53	Vuillemin, J., 137
height, 52	Vygen, J., 232
implicitly defined, 129	
interior node, 52	weak <mark>ly</mark> antisymmetric <mark>, 265</mark>
ordered, 53	Weg <mark>e</mark> ner, I., 54, 142
representation, 136	Wegman, M., 97
root, <b>52</b>	Weidling, C., 97
sorting tree, 106	Westbrook, J., 232
traversal, 53	while, 28
triangle inequality, <b>230</b> , 250	Wickremsinghe, R., 123
trie, see under sorted sequence	Wilhelm, R., 58
triple, 27	Williams, J. W. J., 129
true, <b>24</b>	Winkel, S., 125, 142
truth value, 24	witness, <i>see</i> algorithm design, certificate
Tsitsiklis, J. N., 262	Wolsey, L., 248
TSP, see traveling salesman problem	word, see machine word
tuple, <b>27</b> , 100	worst case, see under running time
type, <b>26</b>	
	XOR (⊕), <b>24</b> , 203
Udupa, R., 123	
Ullman, J., 165	Zagha, M., 125

Zang, I., 215 Zelikowski, A., 229 Ziegelmann, M., 21: Ziviani, N., 91 Zlotowski, O., 171 Zwick, U., 143, 232