

Algorithms Cheat Sheet

Time Complexity

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Introduction

Mathematical Operations

Arithmetics

Operation	Algorithm	Input	Output	Complexity
Addition	Schoolbook	Two n -digit numbers matrices	One $n + 1$ -digit number	$O(n)$
Subtraction	Schoolbook	Two n -digit numbers matrices	One $n + 1$ -digit number	$O(n)$
Multiplication	Schoolbook	Two n -digit numbers matrices	One $2n$ -digit number	$O(n^2)$
	3-way Toom-Cook algorithm	Two n -digit numbers matrices	One $2n$ -digit number	$O(n^{\log_3 5}) \approx O(n^{1.465})$
	k-way Toom-Cook algorithm	Two n -digit numbers matrices	One $2n$ -digit number	$O\left(n^{\frac{\log(2k-1)}{\log k}}\right)$
	Mixed-level Toom-Cook algorithm	Two n -digit numbers matrices	One $2n$ -digit number	$O(n2^{\sqrt{2} \log n} \log n)$
	Karatsuba algorithm	Two n -digit numbers matrices	One $2n$ -digit number	$O(n^{\log_2 3}) \approx O(n^{1.585})$
	Schönhage–Strassen algorithm	Two n -digit numbers matrices	One $2n$ -digit number	$O(n \log n \log \log n)$
	Harvey-Hoeven algorithm	Two n -digit numbers matrices	One $2n$ -digit number	$O(n \log n)$
	Pointer machine ¹	Two n -digit numbers matrices	One $2n$ -digit number	$O(n)$
	Unit Cost RAM machine ¹	Two n -digit numbers matrices	One $2n$ -digit number	$O(n)$
Division	Schoolbook	Two n -digit numbers matrices	One n -digit number	$O(n^2)$
	Burnikel–Ziegler Divide-and-Conquer ²	Two n -digit numbers matrices	One n -digit number	$O(M(n) \log n)$
	Newton–Raphson division ²	Two n -digit numbers matrices	One n -digit number	$O(M(n))$
Square root	Newton’s method ²	One n -digit number	One n -digit number	$O(M(n))$
Modular exponentiation	Repeated multiplication and reduction ²	Two n -digit integers, k -bit exponent	One n -digit integer	$O(M(n)2^k)$
	Exponentiation by squaring ²	Two n -digit integers, k -bit exponent	One n -digit integer	$O(M(n)k)$
	Exponentiation with Montgomery reduction ²	Two n -digit integers, k -bit exponent	One n -digit integer	$O(M(n)k)$

¹ Theoretical model only

² $M(n)$ - The complexity of an implemented multiplication algorithm

Matrix Algebra

Operation	Algorithm	Input	Output	Complexity
Multiplication	Schoolbook	Two $n \times n$ matrices	One $n \times n$ matrix	$O(n^3)$
	Strassen's	Two $n \times n$ matrices	One $n \times n$ matrix	$O(n^{\log_2 7}) = O(n^{2.807})$
	Coppersmith-Winograd	Two $n \times n$ matrices	One $n \times n$ matrix	$O(n^{2.376})$
	Alman-Williams	Two $n \times n$ matrices	One $n \times n$ matrix	$O(n^{2.3728596})$
	Duan, Wu, Zhou	Two $n \times n$ matrices	One $n \times n$ matrix	$O(n^{2.3719})$
	Williams, Xu, Xu, Zhou	Two $n \times n$ matrices	One $n \times n$ matrix	$O(n^{2.3716})$
Inversion	Schoolbook	One $n \times m$ matrix, one $m \times p$ matrix	One $n \times p$ matrix	$O(nmp)$
	Gauss-Jordan elimination	One $n \times n$ matrix	One $n \times n$ matrix	$O(n^3)$
	Strassen algorithm	One $n \times n$ matrix	One $n \times n$ matrix	$O(n^{2.807})$
	Coppersmith-Winograd algorithm	One $n \times n$ matrix	One $n \times n$ matrix	$O(n^{2.376})$
	Optimised CW algorithm	One $n \times n$ matrix	One $n \times n$ matrix	$O(n^{2.373})$
SVD	Bidiagonalization, QR algorithm	One $m \times n$ matrix ($m \leq n$)	One $m \times m$	$O(m^2n)$
			One $m \times n$ matrix	
	Laplace expansion	One $n \times n$ matrix	One number	$O(n!)$
	Division free algorithm	One $n \times n$ matrix	One number	$O(n^4)$
	LU decomposition	One $n \times n$ matrix	One number	$O(n^3)$
	Bareiss algorithm	One $n \times n$ matrix	One number	$O(n^3)$
Back substitution	Fast matrix multiplication	One $n \times n$ matrix	One number	$O(n^{2.373})$
	Back substitution algorithm	Triangular matrix	n solutions	$O(n^2)$

Polynomials

Operation	Algorithm	Input	Output	Complexity
Polynomial evaluation	Direct	One polynomial of degree n and integer coefficients	One number	$O(n)$
	Horner's algorithm	One polynomial of degree n and integer coefficients	One number	$O(n)$
Polynomial gcd	Euclid's algorithm	Two polynomials of degree n and integer coefficients	One number	$O(n^2)$
	Lehmer's algorithm (Fast Euclidean) ³	Two polynomials of degree n and integer coefficients	One number	$O(M(n) \log n)$

³ $M(n)$ - The complexity of an implemented multiplication algorithm

Number theory

Operation	Algorithm	Input	Output	Complexity
Greatest common divisor	Euclidean algorithm	Two n-digit integers	One integer	$O(n^2)$
	Binary GCD	Two n-digit integers	One integer	$O(n^2)$
	Left/right k-ary binary GCD	Two n-digit integers	One integer	$O(\frac{n^2}{\log n})$
	Stehle-Zimmermann algorithm ⁴	Two n-digit integers	One integer	$O(M(n) \log n)$
	Schönhage algorithm ⁴	Two n-digit integers	One integer	$O(M(n) \log n)$
Jacobi symbol	Stehle-Zimmermann algorithm ⁴	Two n-digit integers	0, -1 or 1	$O(M(n) \log n)$
	Schönhage algorithm ⁴	Two n-digit integers	0, -1 or 1	$O(M(n) \log n)$
Factorial	Bottom-up multiplication ⁴	One positive integer less than n	One integer	$O(M(n^2) \log n)$
	Binary splitting ⁴	One positive integer less than n	One integer	$O(M(n \log n) \log n)$
	Exponentiation of the prime factors of n^4	One positive integer less than n	One integer	$O(M(n \log n) \log \log n)$
	Exponentiation of the prime factors of n^4	One positive integer less than n	One integer	$O(M(n \log n))$
Primality test	AKS primality test n	n digit integer	True or false	$O(n^{6+O(1)})$
	AKS primality test with Agrawal's conjecturen	n digit integer	True or false	$O(n^3)$
	Elliptic curve test ⁵ - heuristical approach	n digit integer	True or false	$O(n^{4+\epsilon})$
	Baillie-PSW test ⁵	n digit integer	True or false	$O(n^{2+\epsilon})$
	Miller-Rabin test ⁵ ⁶	n digit integer	True or false	$O(kn^{2+\epsilon})$
	Solovay-Strassen test ⁵ ⁶	n digit integer	True or false	$O(kn^{2+\epsilon})$
Integer factorisation	General number field sieve ⁵	b -bit input integer	A set of factors	$O((1 + \epsilon)^b)$
	Shor's algorithm ⁴ ⁷	b -bit input integer	A set of factors	$O(M(b)b)$

⁴ $M(n)$ - The complexity of an implemented multiplication algorithm

⁵ ϵ - a positive constant

⁶ k - a positive constant

⁷ Theoretical model, on quantum computer

Additional Operations

Operation	Algorithm	Input	Output	Complexity
Discrete Fourier transform	Schoolbook	Size n data sequence	Set of complex number	$O(n^2)$
	Fast Fourier transform	Size n data sequence	Set of complex number	$O(n \log n)$
Golden ration	Newton's method ⁸			$O(M(n))$
Square root of 2	Newton's method ⁸			$O(M(n))$
Euler's number	Taylor series binary splitting of the exp. function ⁸			$O(M(n) \log n)$
	Newton inversion of the natural logarithm ⁸			$O(M(n) \log n)$
Pi	Arctan series binary splitting in Machin's formula ⁸			$O(M(n) \log^2 n)$
	Gauss-Legendre algorithm ⁸			$O(M(n) \log n)$
Euler's constant	Sweeney's method ⁸			$O(M(n) \log^2 n)$
Gamma function	Approx. of the incomplete gamma function ⁸	n digit number		$O(M(n)n^{\frac{1}{2}} \log^2 n)$
	Hypergeometric series ⁸	Fixed ration number		$O(M(n) \log^2 n)$
Hypergeometric function	Borwein and Borwein ⁸	n -digit number		$O(M(n)n^{\frac{1}{2}} \log^2 n)$
	Hypergeometric series ⁸	Fixed rational number		$O(M(n) \log^2 n)$
Taylor series	Repeated argument reduction ^{8 9}			$O(M(n)n^{\frac{1}{2}})$
	FFT-based acceleration ^{8 9}			$O(M(n)n^{\frac{1}{3}} \log^2 n)$
	Binary splitting + bit-burst ^{8 9}			$O(M(n) \log^2 n)$
Arithmetic-geometric mean iteration	Arithmetic-geometric mean iteration ^{8 9}			$O(M(n) \log n)$

⁸ $M(n)$ - The complexity of an implemented multiplication algorithm

⁹ Aplicability: exp. log, sin, cos, arctan

Common Operations on Basic Data Structures

Data Structure	Operation	Average Time Complexity	Worst Time Complexity
Array	Access	$O(1)$	$O(1)$
	Deletion	$O(n)$	$O(n)$
	Insertion	$O(n)$	$O(n)$
	Search	$O(n)$	$O(n)$
Doubly-Linked List	Access	$O(n)$	$O(n)$
	Deletion	$O(1)$	$O(1)$
	Insertion	$O(1)$	$O(1)$
	Search	$O(n)$	$O(n)$
Hash Table	Deletion	$O(1)$	$O(n)$
	Insertion	$O(1)$	$O(n)$
	Search	$O(1)$	$O(n)$
Queue	Access	$O(n)$	$O(n)$
	Deletion	$O(1)$	$O(1)$
	Insertion	$O(1)$	$O(1)$
	Search	$O(n)$	$O(n)$
Singly-Linked List	Access	$O(n)$	$O(n)$
	Deletion	$O(1)$	$O(1)$
	Insertion	$O(1)$	$O(1)$
	Search	$O(n)$	$O(n)$
Skip List	Access	$O(\log n)$	$O(n)$
	Deletion	$O(\log n)$	$O(n)$
	Insertion	$O(\log n)$	$O(n)$
	Search	$O(\log n)$	$O(n)$
Stack	Access	$O(n)$	$O(n)$
	Deletion	$O(1)$	$O(1)$
	Insertion	$O(1)$	$O(1)$
	Search	$O(n)$	$O(n)$

Common Operations on Trees Data Structures

Data Structure	Operation	Average Time Complexity	Worst Time Complexity
AVL Tree	Access	$O(\log n)$	$O(\log n)$
	Deletion	$O(\log n)$	$O(\log n)$
	Insertion	$O(\log n)$	$O(\log n)$
	Search	$O(\log n)$	$O(\log n)$
Binary Search Tree	Access	$O(\log n)$	$O(n)$
	Deletion	$O(\log n)$	$O(n)$
	Insertion	$O(\log n)$	$O(n)$
	Search	$O(\log n)$	$O(n)$
B-Tree	Access	$O(\log n)$	$O(\log n)$
	Deletion	$O(\log n)$	$O(\log n)$
	Insertion	$O(\log n)$	$O(\log n)$
	Search	$O(\log n)$	$O(\log n)$
Cartesian Tree	Deletion	$O(\log n)$	$O(n)$
	Insertion	$O(\log n)$	$O(n)$
	Search	$O(\log n)$	$O(n)$
KD Tree	Access	$O(\log n)$	$O(n)$
	Deletion	$O(\log n)$	$O(n)$
	Insertion	$O(\log n)$	$O(n)$
	Search	$O(\log n)$	$O(n)$
Red-Black Tree	Access	$O(\log n)$	$O(\log n)$
	Deletion	$O(\log n)$	$O(\log n)$
	Insertion	$O(\log n)$	$O(\log n)$
	Search	$O(\log n)$	$O(\log n)$
Splay Tree	Deletion	$O(\log n)$	$O(\log n)$
	Insertion	$O(\log n)$	$O(\log n)$
	Search	$O(\log n)$	$O(\log n)$

Heap - Common Operations

Data Structure	Operation	Complexity
Binary Heap	Find Max	$O(1)$
	Extract Max	$O(\log n)$
	Increase Key	$O(\log n)$
	Insert	$O(\log n)$
	Delete	$O(\log n)$
	Merge	$O(n + m)$
Binomial Heap	Find Max	$O(1)$
	Extract Max	$O(\log n)$
	Increase Key	$O(\log n)$
	Insert	$O(1)$
	Delete	$O(\log n)$
	Merge	$O(\log n)$
Fibonacci Heap	Find Max	$O(1)$
	Extract Max	$O(\log n)$
	Increase Key	$O(1)$
	Insert	$O(1)$
	Delete	$O(\log n)$
	Merge	$O(1)$
Pairing Heap	Find Max	$O(1)$
	Extract Max	$O(\log n)$
	Increase Key	$O(\log n)$
	Insert	$O(1)$
	Delete	$O(\log n)$
	Merge	$O(1)$

Sorting Algorithms

Name	Best	Average	Worst
Block sort	$O(n)$	$O(n \log n)$	$O(n \log n)$
Bubble sort	$O(n)$	$O(n^2)$	$O(n^2)$
Bucket sort ¹⁰	$O(n + k)$	$O(n + k)$	$O(n^2)$
Cocktail shaker sort	$O(n)$	$O(n^2)$	$O(n^2)$
Comb sort ¹¹	$O(n \log n)$	$O(n^2 / 2^p)$	$O(n^2)$
Counting sort ¹²	$O(n + k)$	$O(n + k)$	$O(n + k)$
Cubesort	$O(n)$	$O(n \log n)$	$O(n \log n)$
Cycle sort	$O(n^2)$	$O(n^2)$	$O(n^2)$
Exchange sort	$O(n^2)$	$O(n^2)$	$O(n^2)$
Gnome sort	$O(n^2)$	$O(n^2)$	$O(n^2)$
In-place merge sort	$O(n \log n)$	-	$O(n \log^2 n)$
Insertion sort	$O(n)$	$O(n^2)$	$O(n^2)$
Introsort	$O(n \log n)$	$O(n \log n)$	$O(n \log n)$
Heapsort	$O(n \log n)$	$O(n \log n)$	$O(n \log n)$
Library sort	$O(n \log n)$	$O(n \log n)$	n^2
Merge sort	$O(n \log n)$	$O(n \log n)$	$O(n \log n)$
Odd-even sort	$O(n)$	$O(n^2)$	$O(n^2)$
Patience sort	$O(n)$	$O(n \log n)$	$O(n \log n)$
Quicksort	$O(n \log n)$	$O(n \log n)$	$O(n^2)$
Radix sort ¹³	$O(nd)$	$O(nd)$	$O(nd)$
Selection sort	$O(n^2)$	$O(n^2)$	$O(n^2)$
Shellsort	$O(n \log n)$	$O(n \log^2 n)$	$O(n \log^2 n)$
Smoothsort	$O(n)$	$O(n \log n)$	$O(n \log n)$
Strand sort	$O(n)$	$O(n^2)$	$O(n^2)$
Timsort	$O(n)$	$O(n \log n)$	$O(n \log n)$
Tournament sort	$O(n \log n)$	$O(n \log n)$	$O(n \log n)$
Tree (balanced) sort	$O(n \log n)$	$O(n \log n)$	$O(n \log n)$
Tree (unbalanced) sort	$O(n \log n)$	$O(n \log n)$	$O(n^2)$

¹⁰ k - number of buckets
¹¹ p - number of increments
¹² k - range of input
¹³ d - max key lenght

Searching

Graphs

Data Structure Operations

Data Structure	Operation	Complexity
Adjacency list	Storage	$O(V + E)$
	Add vertex	$O(1)$
	Add edge	$O(1)$
	Remove vertex	$O(V + E)$
	Remove edge	$O(E)$
	Query	$O(V)$
Adjacency matrix	Storage	$O(V ^2)$
	Add vertex	$O(V ^2)$
	Add edge	$O(1)$
	Remove vertex	$O(V ^2)$
	Remove edge	$O(1)$
	Query	$O(1)$
Incidence list	Storage	$O(V + E)$
	Add vertex	$O(1)$
	Add edge	$O(1)$
	Remove vertex	$O(E)$
	Remove edge	$O(E)$
	Query	$O(E)$
Incidence matrix	Storage	$O(V \times E)$
	Add vertex	$O(V \times E)$
	Add edge	$O(V \times E)$
	Remove vertex	$O(V \times E)$
	Remove edge	$O(V \times E)$
	Query	$O(E)$

Graph Search Algorithms

Operation	Algorithm	Input	Comment	Complexity
Explicit Graph Search	Depth First Search	V - vertices, E - edges		$O(V + E)$
Implicit Graph Search	Depth First Search	b - branching factor, d - depth		$O(b^d)$
Explicit Graph Search	Breadth First Search	V - vertices, E - edges		$O(V + E)$
Implicit Graph Search	Breadth First Search	b - branching factor, d - depth		$O(b^d)$
Shortest Path	Dijkstra's Algorithm	V - vertices, E - edges	Priority queue/heap	$O(V + E \log V)$
Shortest Path	Dijkstra's Algorithm	V - vertices, E - edges	Array	$O(V ^2)$

Other Graph Algorithms

Operations on Strings

Bibliography

References

- [1] Cormen T. H., Leiserson C. E. - Introduction to Algorithms, fourth edition, MIT Press, 2022.
- [2] Sedgewick R. - Algorithms, Addison Wesley Publishing Company, 1988.
- [3] Sedgewick R., Wayne K. - Algorithms, Princeton University, 2011.