DISTINGUISHING PRIME NUMBERS FROM COMPOSITE NUMBERS: THE STATE OF THE ART IN 2004

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		$1+o(1)$	$2+o(1)$	$3+o(1)$	$4+o(1)$	$5+o(1)$	$6+o(1)$	$O(1)$	$O(\lg\lg\lg n)$	big
	big	$-\infty$	$-\infty$	$-\infty$	$-\infty$	$-\infty$	$-\infty$	$-\infty$	$-\infty$	$-\infty$
	$O(1)$		1966	1966	1966	1966	1966	1966	1966	$-\infty$
	$2+o(1)$		1966	1966	1966	1966	1966	1966	1966	$-\infty$
rc	$o(1)$						2004	2002	1983	$-\infty$

		$1+o(1)$	$2+o(1)$	$3+o(1)$	$4+o(1)$	$5+o(1)$	$6+o(1)$	$O(1)$	$O(\lg\lg\lg n)$	big
	big	$-\infty$	$-\infty$	$-\infty$	$-\infty$	$-\infty$	$-\infty$	$-\infty$	$-\infty$	$-\infty$
	$O(1)$				2004	2004	2004	2002	1983	$-\infty$
dc	$o(1)$						2004	2002	1983	$-\infty$

		$1+o(1)$	$2+o(1)$	$3+o(1)$	$4+o(1)$	$5+o(1)$	$6+o(1)$	$O(1)$	$O(\lg\lg\lg n)$	big
dpc							2004	2002	1983	$-\infty$

		$1+o(1)$	$2+o(1)$	$3+o(1)$	$4+o(1)$	$5+o(1)$	$6+o(1)$	$O(1)$	$O(\lg\lg\lg n)$	big
dp	$o(1)$						2004	2002	1983	$-\infty$
	big		1987	1914	1914	1914	1914	1914	1914	$-\infty$

		$1+o(1)$	$2+o(1)$	$3+o(1)$	$4+o(1)$	$5+o(1)$	$6+o(1)$	$O(1)$	$O(\lg\lg\lg n)$	big
rp	$o(1)$						2004	2002	1983	$-\infty$
	$2+o(1)$				2003	2003	2003	2002	1983	$-\infty$
	$O(1)$			1992	1992	1992	1992	1992	1983	$-\infty$
	big		1987	1914	1914	1914	1914	1914	1914	$-\infty$

		$1+o(1)$	$2+o(1)$	$3+o(1)$	$4+o(1)$	$5+o(1)$	$6+o(1)$	$O(1)$	$O(\lg\lg\lg n)$	big
?p	$o(1)$						2002	2002	1983	$-\infty$
	$2+o(1)$				2003	2003	2002	2002	1983	$-\infty$
	$4+o(1)$			1990	1990	1990	1990	1990	1983	$-\infty$
	$5+o(1)$			1988	1988	1988	1988	1988	1983	$-\infty$
	$O(1)$			1986	1986	1986	1986	1986	1983	$-\infty$
	big		1987	1914	1914	1914	1914	1914	1914	$-\infty$

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Abstract. This paper compares 21 methods to distinguish prime numbers from composite numbers. It answers the following questions for each method: Does the method certify primality? Conjecturally certify primality? Certify compositeness? Are certificates conjectured to exist for all inputs? Proven to exist for all inputs? Found deterministically for all inputs? Is a certificate verified in essentially linear time? Essentially quadratic time? Et cetera. Is a certificate found immediately? In essentially linear time? Essentially quadratic time? Et cetera. In brief, how does the method work? When and where was the method published?

1. Introduction

This paper summarizes fourteen methods to prove that an integer is prime, three additional methods to prove that an integer is prime if certain conjectures are true, and four methods to prove that an integer is composite.

The table in Section 2 of this paper has one row for each method, with five columns:

- "Method": a brief summary of a theorem encapsulating the method. For example, one method is "if n is not a b-prp, i.e., does not divide $b^n - b$, then n is composite." The target integer is always n. An auxiliary input, such as b in this example, is called a **certificate**. This column includes various credits, such as "1986 [39] Goldwasser Kilian" for a method published in 1986 in [39] by Goldwasser and Kilian. When a method is published by one person with credit to another, the second person is named; for example, Lenstra and Lenstra in [56, Section 5.10] published a primality-proving method with credit to Shallit, so the table says "1990 [56, Section 5.10] Shallit."
- "Effect of certificate": what the method tells you about the target integer n. Either "proves primality" or "conjecturally certifies primality" or "proves compositeness." This column sometimes includes separate proof credits; for example, the table says "1936 [46] Hasse" for the Goldwasser-Kilian primality-proving method, because the primality proofs rely on a theorem published by Hasse in 1936.
- "Certificate exists for": which integers can be handled by the method. Either "every prime" or "conjecturally every prime" or "every composite" or "nearly every composite."
- "Time to verify certificate": how quickly one can check whether an auxiliary input is a certificate for n. For example, $(\lg n)^{1+o(1)}$ or $(\lg n)^{2+o(1)}$ or $(\lg n)^{O(\lg \lg \lg n)}$. This column sometimes includes separate credits for proofs of, or improvements in, the speed of certificate verification; for example, the table says "1969 [38] Goldfeld" for the Agrawal-Kayal-Saxena primality-proving method, because the upper bound for certificate-verification time relies on a theorem published by Goldfeld in 1969.
- "Time to find certificate," at the same level of detail. The word "random" indicates a certificate-finding algorithm that uses randomness. This column sometimes includes separate credits; for example, the table says "1985 [86] Schoof" for the Goldwasser-Kilian primality-proving method, because the method finds certificates using an algorithm published by Schoof in 1985.

Complexity measures. When I say "time" in this paper, I mean "time on a 2-tape Turing machine, using fast subroutines for arithmetic."

A 2-tape Turing machine is a typical example of a conventional von Neumann computer. Extra tapes, random access to memory, etc. often save time, but not enough to matter at the level of detail of run times in this paper. I have followed the (questionable) tradition of measuring time and ignoring space.

Fast subroutines for arithmetic are surveyed in my paper [17]. In particular, integer multiplication, division, and gcd can be done in essentially linear time, as shown by Toom in [90], Cook in [33, pages 81–86], and Knuth in [51] respectively.

Beware that the primality/compositeness literature often uses quadratic-time subroutines for arithmetic—usually because the authors were writing before the essentially-linear-time algorithms were known, but sometimes because the authors inexplicably refused to take advantage of the essentially-linear-time algorithms. In every case I have retroactively substituted essentially-linear-time algorithms.

Information presented in the chart. A compressed chart appears on the first page of this paper, summarizing the results achieved by various methods. Thanks to Eric Bach for suggesting that I include a chart.

The chart is, conceptually, three-dimensional. The first dimension indicates what the certificates do—for example, prove primality—and how reliably the certificates are found; the second dimension indicates how quickly certificates are found; the third dimension indicates how quickly certificates are verified. Specifically:

- In the outer labels (rc, dc, dpc, dp, rp, ?p), "p" means that certificates prove primality; "c" means that certificates prove compositeness; "?" means that certificates are conjectured to be found for every n (every prime n for primality-proving methods, or every composite n for compositeness-proving methods); "r" means that certificates are provably found for every n; "d" means that certificates are provably deterministically found for every n. Certificates not believed to exist for every n are not included in the chart; certificates that are merely conjectured to imply primality are not included in the chart.
- The row labels ($o(1)$, $2+o(1)$, $4+o(1)$, $5+o(1)$, $O(1)$, big) are proven upper bounds for exponents in times to (provably deterministically, or provably randomly, or conjecturally) find certificates.
- The column labels ($1+o(1)$, $2+o(1)$, $\ldots$, $6+o(1)$, $O(1)$, $O(\lg\lg\lg n)$, big) are proven upper bounds for exponents in times to (provably deterministically) verify certificates.

Each chart entry is the publication year for a method achieving that combination of speed and results. For example, the entry 1992 at position $(\mathrm{rp}, O(1), 3+o(1))$ refers to a method published in 1992 that proves primality of every prime n, provably finds certificates (perhaps using randomness) in time $(\lg n)^{O(1)}$, and provably verifies certificates (deterministically) in time $(\lg n)^{3+o(1)}$: namely, the Adleman-Huang method in [4] of proving primality with genus-2-hyperelliptic-curve factors.

Often one cares only about the total time to find and verify certificates. Chart entries are separated by horizontal or vertical lines if their total times are different at this level of detail. For example, 1990 at position $(?\mathrm{p}, 4+o(1), 4+o(1))$ indicates that a method published in 1990 is conjectured to find and verify a certificate of primality in total time $(\lg n)^{4+o(1)}$; 2003 at position $(?\mathrm{p}, 2+o(1), 4+o(1))$ has the same total time $(\lg n)^{4+o(1)}$; there is no line separating these entries in the chart.

Here are the methods shown in the chart:

- $(\mathrm{dc}, \mathrm{big}, 1+o(1))$ $-\infty$, proving compositeness with factorization. Can also be used to prove primality: $(\mathrm{dpc}, o(1), \mathrm{big})$. "PRIMES is in coNP" refers to $(\mathrm{dc}, \mathrm{big}, O(1))$.
- $(\mathrm{dp}, \mathrm{big}, 3+o(1))$ 1914 [78] Pocklington, proving primality with unit-group factors. "PRIMES is in NP" refers to $(\mathrm{dp}, \mathrm{big}, O(1))$.
- $(\mathrm{rc}, 2+o(1), 2+o(1))$ 1966 [9] Artjuhov, proving compositeness with Fermat. "PRIMES is in coRP" refers to $(\mathrm{rc}, O(1), O(1))$.
- $(\mathrm{dpc}, o(1), O(\lg\lg\lg n))$ 1983 [5] Adleman Pomerance Rumely (announced in 1979), proving primality with unit-group factors.
- $(?\mathrm{p}, O(1), 3+o(1))$ 1986 [39] Goldwasser Kilian, proving primality with elliptic-curve factors.
- $(\mathrm{dp}, \mathrm{big}, 2+o(1))$ 1987 [80] Pomerance, proving primality with elliptic-curve factors.
- $(?\mathrm{p}, 5+o(1), 3+o(1))$ 1988 [69] Atkin, proving primality with elliptic-curve factors.
- $(?\mathrm{p}, 4+o(1), 3+o(1))$ 1990 [56, Section 5.10] Shallit, proving primality with elliptic-curve factors.
- $(\mathrm{rp}, O(1), 3+o(1))$ 1992 [4] Adleman Huang, proving primality with genus-2-hyperelliptic-curve factors. "PRIMES is in RP" refers to $(\mathrm{rp}, O(1), O(1))$.
- $(\mathrm{dpc}, o(1), O(1))$—"PRIMES is in P"—2002 [6] Agrawal Kayal Saxena, proving primality with combinatorics. Also $(?\mathrm{p}, o(1), 6+o(1))$.
- $(\mathrm{rp}, 2+o(1), 4+o(1))$ 2003 [18] Bernstein, proving primality with combinatorics.
- $(\mathrm{dpc}, o(1), 6+o(1))$ 2004 [44, Section 7] Lenstra Pomerance (announced in 2003.03), proving primality with combinatorics. Can also be used to prove compositeness: $(\mathrm{dc}, 6+o(1), 4+o(1))$.

The chart poses several challenges. For example, can we find an $(\mathrm{rp}, \mathrm{big}, 1+o(1))$ algorithm—an algorithm that verifies a certificate of primality in essentially linear time? Similarly, can we find an $(\mathrm{rc}, O(1), 1+o(1))$ algorithm—an algorithm that finds certificates of compositeness in polynomial time and verifies them in essentially linear time? Can we find a $(?\mathrm{p}, 3+o(1), 3+o(1))$ algorithm—an algorithm that proves primality in, conjecturally, essentially cubic time?

Different perspectives. This paper discusses time at a particular level of detail—not always enough detail to figure out which method is fastest. Is proving primality with combinatorics faster than proving primality with elliptic-curve factors? To answer this question, one needs to carry out a more detailed run-time analysis; what this paper says is that the first method (provably) takes essentially quartic time, and that the second method (conjecturally) takes essentially quartic time.

This paper's viewpoint is ruthlessly asymptotic, considering only what happens for *extremely large* values of n. For example, any constant is viewed as being better than $\lg\lg\lg n$. But $\lg\lg\lg n$ is actually rather small for *reasonable* values of n. Is proving primality with unit-group factors faster, for reasonable values of n, than proving primality with elliptic-curve factors? The exponent bounds $O(\lg\lg\lg n)$

and $4 + o(1)$ are of no use in answering this question; one needs a much more detailed run-time analysis.

Small values of n also raise interest in "non-uniform" algorithms: algorithms that perform precomputations for a range of inputs n, with the precomputation time measured separately. For example, a positive integer n below 2^{48} is prime if and only if it is a 2-sprp, 3-sprp, 5-sprp, 7-sprp, 11-sprp, 13-sprp, and 17-sprp; Jaeschke in [49] proved this by a large computation. The test of [61, Theorem 2] is somewhat less efficient but uses less precomputation; this test, in combination with a large "pseudosquare" computation by Williams and Wooding using my algorithm in [15, Section 4], now allows primes up to 2^{100} to be quickly proven prime.

This paper focuses primarily on upper bounds for time. Some algorithms, for some inputs, take much less time than the upper bounds indicate. For example, for *many* primes n, Pocklington's 1914 method finds a certificate of primality for n in polynomial time and verifies the certificate in essentially quadratic time. This set of primes n has been considerably expanded, thanks to an application of lattice-basis reduction by Lenstra, Konyagin, Pomerance, Coppersmith, Howgrave-Graham, and Nagaraj; see my exposition [19, Section 5], or the original papers [57], [52], and [47, Section 5.5]. This information is absent from the chart in this paper, and is covered only briefly in the table.

2. The table

Method	Effect of certificate	Certificate exists for	Time to verify certificate	Time to find certificate
proving compositeness with factorization: if b divides n and $1 < b < n$ then n is composite	proves compositeness	every composite n	$(\lg n)^{1+o(1)}$	very slow; but $(\lg n)^{O(1)}$ for most n
proving compositeness with Fermat: if n is not a b-prp, i.e., does not divide $b^n - b$, then n is composite	proves compositeness	nearly every composite n; however, there are infinitely many composites n that are all-b-prp (1994 [7] Alford Granville Pomerance)	$(\lg n)^{2+o(1)}$	random $(\lg n)^{2+o(1)}$

Method	Effect of certificate	Certificate exists for	Time to verify certificate	Time to find certificate
if n is not a b-sprp, i.e., does not divide any of the most obvious factors of $b^n - b$, then n is composite (1966 [9] Artjuhov)	proves compositeness	every composite n	$(\lg n)^{2+o(1)}$	random $(\lg n)^{2+o(1)}$ (1976 [84] Rabin, independently 1980 [67] Monier, independently 1982 [11] Atkin Larson; inferior variant: 1976 [55] Lehmer, independently 1977 [89] Solovay Strassen; other variants: 1998 [42] Grantham, 2001 [43] Grantham, 2000 [73] Müller, 2001 [74] Müller, 2003 [34] Damgard Frandsen)
conjecturally testing primality: if n is a b-sprp for every prime number b between 1 and $\lceil \lg n \rceil^2$, then n seems to be prime (basic idea: 1975 [65] Miller)	conjecturally certifies primality; conjecture follows from GRH (1985 [13] Bach; $35 \lceil \lg n \rceil^2$ announced but not proven 1979 Oesterlé; $O(\lceil \lg n \rceil^2)$, without explicit O constant: 1952 [8] Ankeny, 1971 [68] Montgomery, 1978 [94] Vélu)	every prime n	$(\lg n)^{4+o(1)}$	instant
if n is a b-sprp for the first $2 \lceil \lg n \rceil$ prime numbers b, then n seems to be prime (folklore; simpler variant: 1995 [61, Theorem 2] Lukes Patterson Williams)	conjecturally certifies primality	every prime n	$(\lg n)^{3+o(1)}$	instant

Method	Effect of certificate	Certificate exists for	Time to verify certificate	Time to find certificate
if n is a 2-sprp and passes a similar quadratic test, then n seems to be prime (1980 [14] Baillie Wagstaff, 1980 [81] Pomerance Selfridge Wagstaff; variant also including a cubic test: 1998 [10] Atkin)	conjecturally certifies primality; conjecture is implausible for very large n (1984 [79] Pomerance), but no counterexamples are known	every prime n	$(\lg n)^{2+o(1)}$	instant
proving primality with unit-group factors: if $b^{n-1} = 1$ in $\mathbf{Z}/n$, and $b^{(n-1)/q} - 1$ is nonzero in $\mathbf{Z}/n$ for every prime divisor q of $n - 1$, then n is prime (1876 [59] [60] Lucas, except that the switch from "divisor $q > 1$" to "prime divisor q" is from 1927 [53] Lehmer by analogy to 1914 [78] Pocklington)	proves primality	every prime n	at most $(\lg n)^{3+o(1)}$; usually $(\lg n)^{2+o(1)}$	very slow; but conjectured to be $(\lg n)^{O(1)}$ for infinitely many n
if $b^{n-1} = 1$ in $\mathbf{Z}/n$, F is a divisor of $n - 1$, and $b^{(n-1)/q} - 1$ is a unit in $\mathbf{Z}/n$ for every prime divisor q of F, then every divisor of n is in $\{1, F + 1, \dots\}$, so if $(F + 1)^2 > n$ then n is prime (1914 [78] Pocklington); similar test for F down to roughly $n^{1/4}$	proves primality	every prime n	at most $(\lg n)^{3+o(1)}$; usually $(\lg n)^{2+o(1)}$	very slow; but fast for more n's than above; $(\lg n)^{O(1)}$ for infinitely many n (1989 [77] Pintz Steiger Szemeredi; variant: 1992 [35] Fellows Koblitz; another variant: 1997 [52] Konyagin Pomerance)

Method	Effect of certificate	Certificate exists for	Time to verify certificate	Time to find certificate
Pocklington-type test with quadratic extensions of $\mathbf{Z}/n$ (1876 [59] Lucas, 1930 [54] Lehmer, 1975 [72] Morrison, 1975 [88] Selfridge Wunderlich, 1975 [25] Brillhart Lehmer Selfridge)	proves primality	every prime n	at most $(\lg n)^{3+o(1)}$; usually $(\lg n)^{2+o(1)}$	very slow; but fast for more n's than above
Pocklington-type test with higher-degree extensions of $\mathbf{Z}/n$ (degrees 4 and 6: 1976 [97] Williams Judd; general degrees: 1983 [5] Adleman Pomerance Rumely)	proves primality	every prime n	$(\lg n)^{O(\lg \lg \lg n)}$, using distribution of divisors of $n^d - 1$ (1983 [5] Odlyzko Pomerance; weaker bound: 1955 [82] Prachar; best known bound: 2000 [76] Pelikan Pintz Szemeredi); many speedups available (1978 [96] Williams Holte, 1984 [32] Cohen Lenstra, 1985 [30] Cohen Lenstra, 1990 [23] Bosma van der Hulst, 1998 [63] Mihăilescu)	instant
proving primality with elliptic-curve factors: similar test using elliptic curves (1986 [39] Goldwasser Kilian)	proves primality, using bounds on elliptic-curve sizes (1936 [46] Hasse)	nearly every prime n; conjecturally, every prime n	$(\lg n)^{3+o(1)}$	$(\lg n)^{O(1)}$, using polynomial-time elliptic-curve point counting (1985 [86] Schoof); many speedups available (1995 [87] Atkin Elkies; 1995 [58] Lercier Morain)

Method	Effect of certificate	Certificate exists for	Time to verify certificate	Time to find certificate
similar test with elliptic curves having order divisible by a large power of 2 (1987 [80] Pomerance)	proves primality, using bounds on elliptic-curve sizes (1936 [46] Hasse)	every prime n	$(\lg n)^{2+o(1)}$	very slow
similar test with Jacobians of genus-2 hyperelliptic curves (1992 [4] Adleman Huang)	proves primality, using bounds on Jacobian sizes (1948 [95] Weil)	every prime n	at most $(\lg n)^{3+o(1)}$	random $(\lg n)^{O(1)}$, using distribution of primes in interval of width $x^{3/4}$ around x (1979 [48] Iwaniec Jutila), and distribution of Jacobian sizes (1992 [4] Adleman Huang)
similar test with small-discriminant complex-multiplication elliptic curves (1988 [69] Atkin; special cases: 1985 [21] Bosma, 1986 [29] Chudnovsky Chudnovsky)	proves primality, using bounds on elliptic-curve sizes (1936 [46] Hasse)	conjecturally, every prime n	at most $(\lg n)^{3+o(1)}$	at most $(\lg n)^{5+o(1)}$
similar test with small-discriminant complex-multiplication elliptic curves, merging square-root computations for many discriminants (1990 [56, Section 5.10] Shallit)	proves primality, using bounds on elliptic-curve sizes (1936 [46] Hasse)	conjecturally, every prime n	at most $(\lg n)^{3+o(1)}$	at most $(\lg n)^{4+o(1)}$; many speedups available (1988 [69] Morain, 1989 [50] Kaltofen Valente Yui, 1990 [70] Morain, 1993 [12] Atkin Morain, 1998 [71] Morain, 2003 [37] Franke Kleinjung Morain Wirth)

Method	Effect of certificate	Certificate exists for	Time to verify certificate	Time to find certificate
proving primality with combinatorics: if we can write down many elements of a particular subgroup of a prime cyclotomic extension of $\mathbf{Z}/n$ then n is a power of a prime (2002.08 [6] Agrawal Kayal Saxena)	proves primality	every prime n	$(\lg n)^{O(1)}$, using analytic fact that, for some $c > 1/2$, many primes r have prime divisor of $r - 1$ above r^c (1969 [38] Goldfeld); at most $(\lg n)^{12+o(1)}$, using analytic fact that many primes r have prime divisor of $r - 1$ above $r^{2/3}$ (1985 [36] Fouvry); conjecturally $(\lg n)^{6+o(1)}$	instant
variant using arbitrary cyclotomic extensions (2003.01 [16, Theorem 2.3] Lenstra)	proves primality	every prime n	at most $(\lg n)^{12+o(1)}$, using crude bound on distribution of primes (1850 Chebyshev); at most $(\lg n)^{8+o(1)}$, using analytic facts as above; conjecturally $(\lg n)^{6+o(1)}$	instant
variant using cyclotomic extensions with better bound on group structure (2002.12 [62] Macaj, independently 2003 Agrawal)	proves primality	every prime n	at most $(\lg n)^{10.5+o(1)}$, using crude bound on distribution of primes (1850 Chebyshev); at most $(\lg n)^{7.5+o(1)}$, using analytic facts as above; conjecturally $(\lg n)^{6+o(1)}$	instant

Method	Effect of certificate	Certificate exists for	Time to verify certificate	Time to find certificate
variant using random Kummer extensions (2003.01 [18] Bernstein; independently 2003.03 [64] Mihăilescu Avanzi; idea and 2-power-degree case: 2002.12 [20] Berrizbeitia; prime-degree case: 2003.01 [28] Cheng)	proves primality	every prime n	$(\lg n)^{4+o(1)}$, using distribution of divisors of $n^d - 1$ (overkill: 1983 [5] Odlyzko Pomerance)	random $(\lg n)^{2+o(1)}$
variant using Gaussian periods (2004 [44, Section 7] Lenstra Pomerance)	proves primality	every prime n	$(\lg n)^{6+o(1)}$, using various analytic facts	instant
if n fails any of the Fermat-type tests in these methods then n is composite	proves compositeness	every composite n	at most $(\lg n)^{4+o(1)}$, using analytic facts as above	at most $(\lg n)^{6+o(1)}$, using analytic facts as above

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