Extending Babbage's (Non-)Primality Tests

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Abstract We recall Charles Babbage's 1819 criterion for primality, based on simultaneous congruences for binomial coefficients, and extend it to a least-prime-factor test. We also prove a partial converse of his non-primality test, based on a single congruence. Along the way we encounter Bachet, Bernoulli, Bézout, Euler, Fermat, Kummer, Lagrange, Lucas, Vandermonde, Waring, Wilson, Wolstenholme, and several contemporary mathematicians.

Keywords Charles Babbage · Primality test · Binomial coefficient · Congruence
Wolstenholme prime · Lucas's theorem

1 Introduction

Charles Babbage was an English mathematician, philosopher, inventor, mechanical engineer, and "irascible genius" who pioneered computing machines [2, 4, 10, 21–23]. Although he held the Lucasian Chair of Mathematics at Cambridge University from 1828 to 1839, during that period he never resided in Cambridge or delivered a lecture [5, 7, p. 7].

In 1819, he published his only work on number theory, a short paper [1] that begins:

> The singular theorem of Wilson respecting Prime Numbers, which was first published by Waring in his *Meditationes Analyticae* [31, p. 218], and to which neither himself nor its author could supply the demonstration, excited the attention of the most celebrated analysts of the continent, and to the labors of Lagrange [14] and Euler we are indebted for several modes of proof . . . .

Babbage formulated **Wilson's theorem** as a criterion for primality: *an integer* $p > 1$ *is a prime if and only if* $(p - 1)! \equiv -1 \pmod{p}$. (For a modern proof, see Moll [20, p. 66].) He then introduced several such criteria, involving congruences for

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M. B. Nathanson (ed.), *Combinatorial and Additive Number Theory II*,
Springer Proceedings in Mathematics & Statistics 220,
https://doi.org/10.1007/978-3-319-68032-3_19

binomial coefficients (see Granville [11, Sections 1 and 4]). However, some of his claims were unproven or even wrong (as Dubbey points out in [7, pp. 139–141]). One of his valid results is a necessary and sufficient condition for primality, based on a number of simultaneous congruences. Henceforth, let n denote an integer.

Theorem 1 (Babbage's Primality Test) *An integer $p > 1$ is a prime if and only if*

$$\binom{p+n}{n} \equiv 1 \pmod{p} \tag{1}$$

for all n satisfying $0 \le n \le p-1$.

This is of only theoretical interest, the test being slower than trial division.

The "only if" part is an immediate consequence of the beautiful **theorem of Lucas** [15] (see [8, 11, 17, 19] and [20, p. 70]), which asserts that *if p is a prime and the non-negative integers $a = \alpha_0 + \alpha_1 p + \cdots + \alpha_r p^r$ and $b = \beta_0 + \beta_1 p + \cdots + \beta_r p^r$ are written in base p (so that $0 \le \alpha_i, \beta_i \le p-1$ for all i), then*

$$\binom{a}{b} \equiv \prod_{i=0}^{r} \binom{\alpha_i}{\beta_i} \pmod{p}. \tag{2}$$

(Here the convention is that $\binom{\alpha}{\beta} = 0$ if $\alpha < \beta$.) The congruence (1) follows if $0 \le n \le p-1$, for then all the binomial coefficients formed on the right-hand side of (2) are of the form $\binom{\alpha}{\alpha} = 1$, except the last one, which is $\binom{1}{0} = 1$.

However, the theorem was not available to Babbage because when it was published in 1878 he had been dead for seven years.

Lucas's theorem implies more generally that *for p a prime and m a power of p*, the congruences

$$\binom{m+n}{n} \equiv 1 \pmod{p} \qquad (0 \le n \le m-1) \tag{3}$$

hold. A converse was proven in 2013: **Meštrović's theorem** [19] states that *if $m > 1$ and $p > 1$ are integers such that (3) holds, then p is a prime and m is a power of p.* To begin the proof, Meštrović noted that for $n = 1$, the hypothesis gives

$$\binom{m+1}{1} = m+1 \equiv 1 \pmod{p} \quad \Longrightarrow \quad p \mid m.$$

The rest of the proof involves combinatorial congruences modulo prime powers.

As Meštrović pointed out, "the 'if' part of Theorem 1 is an immediate consequence of [his theorem] (supposing a priori [that $m = p$]). Accordingly, [his theorem] may be considered as a generalization of Babbage's criterion for primality."

Here we offer another generalization of Babbage's primality test.

Theorem 2 (Least-Prime-Factor Test) *The least prime factor of an integer $m > 1$ is the smallest natural number ℓ satisfying*

$$\binom{m+\ell}{\ell} \not\equiv 1 \pmod{m}. \tag{4}$$

For that value of ℓ, *the least non-negative residue of* $\binom{m+\ell}{\ell}$ *modulo* m *is* $\frac{m}{\ell}+1$.

The proof is given in Sect. 2.

Babbage's primality test is an easy corollary of the least-prime-factor test. Indeed, Theorem 2 implies a sharp version of Theorem 1 noticed by Granville [11] in 1995.

Corollary 1 (Sharp Babbage Primality Test) *Theorem 1 remains true if the range for* n *is shortened to* $0 \le n \le \sqrt{p}$.

Proof An integer $m > 1$ is a prime if and only if its least prime factor ℓ exceeds $\sqrt{m}$. The corollary follows by setting $m = p$ in Theorem 2. □

To see that *Corollary 1 is sharp in that the range for* n *cannot be further shortened to* $0 \le n \le \sqrt{p} - 1$, let q be any prime and set $p = q^2$. Then p is not a prime, but the least-prime-factor test with $m = p$ and $\ell = q$ implies (1) when $0 \le n \le q - 1$.

Problem 1 Since the "if" part of Babbage's primality test is a consequence both of Meštrović's theorem and of the least-prime-factor test, one may ask, *Is there a common generalization of Meštrović's theorem and Theorem 2*? (Note, though, that the modulus in the former is p, while that in the latter is m.)

Actually, the incongruence (4) holds more generally if the *least* prime factor $\ell \mid m$ is replaced with *any* prime factor $p \mid m$. The following extension of the least-prime-factor test is proven in Sect. 2.

Theorem 3 (i) *Given a positive integer* m *and a prime factor* $p \mid m$, *we have*

$$\binom{m+p}{p} \not\equiv 1 \pmod{m}. \tag{5}$$

(ii) *If in addition* $p^r \mid m$ *but* $p^{r+1} \nmid m$, *where* $r \ge 1$, *then*

$$\binom{m+p}{p} \equiv \frac{m}{p} + 1 \not\equiv 1 \pmod{p^r}. \tag{6}$$

Part (i) is clearly equivalent to the statement that *if* $d > 1$ *divides* m *and* $\binom{m+d}{d} \equiv 1 \pmod{m}$, *then* d *is composite.* As an example, for $m = 260$ and $d = 10$, we have

$$\binom{m+d}{d} = \binom{270}{10} = 479322759878148681 \equiv 1 \pmod{260}.$$

The sequence of integers $m > 1$, for which some integer d (necessarily composite) satisfies

$$d > 1, \qquad d \mid m, \qquad \binom{m+d}{d} \equiv 1 \pmod{m},$$

begins [28, Seq. A290040]

$$m = 260, 1056, 1060, 3460, 3905, 4428, 5000, 5060, 5512, 5860, 6372, 6596, \ldots$$

and the sequence of smallest such divisors d is, respectively, [28, Seq. A290041]

$$d = 10, 264, 10, 10, 55, 18, 20, 10, 52, 10, 18, 34, \ldots . \tag{7}$$

Problem 2 Does Theorem 3 extend to prime power factors, i.e., does (5) also hold when p is replaced with p^k, where $p^k \mid m$ and $k > 1$? In particular, in the sequence (7), is any term d a prime power?

Babbage also claimed a necessary and sufficient condition for primality based on a *single* congruence. But he proved only necessity, so we call it a test for non-primality.

Theorem 4 (Babbage's Non-Primality Test) *An integer $m \geq 3$ is composite if*

$$\binom{2m-1}{m-1} \not\equiv 1 \pmod{m^2}. \tag{8}$$

Our version of his proof is given in Sect. 3.

Not only did Babbage not prove the claimed converse, but in fact it is false. Indeed, *the numbers $m_1 = p_1^2 = 283686649$ and $m_2 = p_2^2 = 4514260853041$ are composite but do not satisfy* (8), where $p_1 = 16843$ and $p_2 = 2124679$ are primes.

Here p_1 (indicated by Selfridge and Pollack in 1964) and p_2 (discovered by Crandall, Ernvall, and Metsänkylä in 1993) are *Wolstenholme primes*, so called by Mcintosh [16] because, while **Wolstenholme's theorem** [32] (see [11, 18, 29] and [20, p. 73]) of 1862 guarantees that *every prime $p \geq 5$ satisfies*

$$\binom{2p-1}{p-1} \equiv 1 \pmod{p^3}, \tag{9}$$

in fact p_1 and p_2 satisfy the congruence in (9) modulo p^4, not just p^3 (see Guy [12, p. 131] and Ribenboim [25, p. 23]).

Note that (9) strengthens Babbage's non-primality test, as Theorem 4 is equivalent to the statement that *the congruence in* (9) *holds modulo p^2 for any prime $p \geq 3$.*

In their solutions to a problem by Segal in the *Monthly*, Brinkmann [26] and Johnson [27] made Babbage's and Wolstenholme's theorems more precise by showing that *every prime $p \geq 5$ satisfies the congruences*

$$\binom{2p-1}{p-1} \equiv 1 - \frac{2}{3}p^3 B_{p-3} \equiv \binom{2p^2-1}{p^2-1} \pmod{p^4},$$

where B_k denotes the kth *Bernoulli number*, a rational number. (See also Gardiner [9] and Mcintosh [16].) Thus, *a prime* $p \geq 5$ *is a Wolstenholme prime if and only if* $B_{p-3} \equiv 0 \pmod{p}$. (The congruence means that p divides the numerator of B_{p-3}.) In that case, the square of that prime, say $m = p^2$, is composite but must satisfy

$$\binom{2m-1}{m-1} \equiv 1 \pmod{m^2},$$

thereby providing a counterexample to the converse of Babbage's non-primality test.

Johnson [27] commented that "interest in [Wolstenholme primes] arises from the fact that in 1857, Kummer proved that the first case of [Fermat's Last Theorem] is true for all prime exponents p such that $p \nmid B_{p-3}$."

We have seen that the converse of Babbage's non-primality test is false. The converse of Wolstenholme's theorem is the statement that *if* $p \geq 5$ *is composite, then* (9) *does not hold.* It is not known whether this is generally true. A proof that it is true for *even* positive integers was outlined by Trevisan and Weber [29] in 2001. In Sect. 3, we fill in some details omitted from their argument and extend it to prove the following stronger result.

Theorem 5 (Converse of Babbage's Non-Primality Test for Even Numbers) *If a positive integer m is even, then*

$$\binom{2m-1}{m-1} \not\equiv 1 \pmod{m^2}. \tag{10}$$

2 Proofs of the Least-Prime-Factor Test and Its Extension

We prove Theorems 2 and 3. The arguments use only mathematics available in Babbage's time.

Proof (Theorem 2) As ℓ is the smallest prime factor of m, if $0 < k < \ell$ then $k!$ and m are coprime. In that case, **Bézout's identity** (proven in 1624 by Bachet in a book with the charming title *Pleasant and Delectable Problems* [3, p. 18, Proposition XVIII]—see [6, Section 4.3]) gives integers a and b with $ak! + bm = 1$. Multiplying Bézout's equation by the number $\binom{m}{k} = m(m-1)\cdots(m-k+1)/k!$ yields

$$am(m-1)\cdots(m-k+1) + bm\binom{m}{k} = \binom{m}{k},$$

so $\binom{m}{k} \equiv 0 \pmod{m}$ if $1 \leq k \leq \ell - 1$. Now, for $n = 0, 1, \ldots, \ell - 1$, **Vandermonde's convolution** [30] (see [20, p. 164]) of 1772 gives

$$\binom{m+n}{n} = \sum_{k=0}^{n} \binom{m}{k}\binom{n}{n-k} \equiv \binom{m}{0}\binom{n}{n} \pmod{m}.$$

(To see the equality, equate the coefficients of x^n in the expansions of $(1+x)^{m+n}$ and $(1+x)^m(1+x)^n$). Thus, we arrive at the congruences

$$\binom{m+n}{n} \equiv 1 \pmod{m} \qquad (0 \le n \le \ell - 1). \tag{11}$$

On the other hand, from the identity

$$\binom{a}{b} = \frac{a}{b}\binom{a-1}{b-1} \tag{12}$$

(to prove it, use factorials), the congruence (11) for $n = \ell - 1$, the integrality of $\frac{m+\ell}{\ell} = \frac{m}{\ell} + 1$, and the inequality $\ell > 1$ (as ℓ is a prime), we deduce that

$$\binom{m+\ell}{\ell} = \frac{m+\ell}{\ell}\binom{m+\ell-1}{\ell-1} \equiv \frac{m}{\ell} + 1 \not\equiv 1 \pmod{m}.$$

Together with (11), this implies the least-prime-factor test. □

Proof (Theorem 3) It suffices to prove (ii). Set

$$g \overset{\text{def}}{=} \gcd((p-1)!, m) \qquad \text{and} \qquad m_p \overset{\text{def}}{=} \frac{m}{g}.$$

Note that

$$p \text{ prime} \implies p \nmid g \implies p^r \mid m_p, \tag{13}$$

since $p^r \mid m$. Bézout's identity gives integers a and b with $a(p-1)! + bm = g$. When $0 < k < p$, multiplying Bézout's equation by $\binom{m}{k}$ yields

$$am(m-1)\cdots(m-k+1)\frac{(p-1)!}{k!} + bm\binom{m}{k} = g\binom{m}{k}$$

with $(p-1)!/k!$ an integer, so $g\binom{m}{k} \equiv 0 \pmod{m}$. Dividing by g gives

$$\binom{m}{k} \equiv 0 \pmod{m_p} \quad (1 \le k \le p-1).$$

Combining this with (12) and Vandermonde's convolution, we get

$$\begin{aligned}\binom{m+p}{p} = \frac{m+p}{p}\binom{m+p-1}{p-1} &= \frac{m+p}{p}\sum_{k=0}^{p-1}\binom{m}{k}\binom{p-1}{p-1-k} \\ &\equiv \frac{m}{p} + 1 \pmod{m_p}.\end{aligned} \tag{14}$$

As $p^{r+1} \nmid m$, we have $p^r \nmid \frac{m}{p}$. Now, (13) and (14) imply (6), as required. □

3 Proofs of Babbage's Non-primality Test and Its Converse for Even Numbers

The following proof is close to the one Babbage gave.

Proof (Theorem 4) Suppose on the contrary that m is prime. If we have $1 \le n \le m-1$, then m divides the numerator of $\binom{m}{n} = m!/n!(m-n)!$ but not the denominator, so $\binom{m}{n} \equiv 0 \pmod{m}$. Thus, by (12) and a famous case of Vandermonde's convolution,

$$2\binom{2m-1}{m-1} = \binom{2m}{m} = \sum_{n=0}^{m} \binom{m}{n}^2 \equiv 1^2 + 1^2 \equiv 2 \pmod{m^2}.$$

But as $m \ge 3$ is odd, (3) contradicts (8). Therefore, m is composite. □

Before giving the proof of Theorem 5, we establish two lemmas. For any positive integer k, let $2^{v(k)}$ denote the highest power of 2 that divides k.

Lemma 1 *If $m \ge n \ge 1$ are integers satisfying $n \le 2^{v(m)}$, then the formula $v(\binom{m}{n}) = v(m) - v(n)$ holds.*

Proof Let $m = 2^r m'$ with m' odd. Note that $v(2^r m' - k) = v(k)$ if $0 < k < 2^r$. (*Proof.* Write $k = 2^t k'$, where $0 \le t = v(k) \le r-1$ and k' is odd. Then $2^{r-t}m' - k'$ is also odd, so $v(2^r m' - k) = v(2^t(2^{r-t}m' - k')) = t = v(k)$.) The logarithmic formula $v(ab) = v(a) + v(b)$ then implies that when $1 \le n \le 2^r$, the exponent of the highest power of 2 that divides the product

$$n!\binom{m}{n} = 2^r m'(2^r m' - 1)(2^r m' - 2) \cdots (2^r m' - (n-1))$$

is $v(n!) + v(\binom{m}{n}) = r + v(1 \cdot 2 \cdots (n-1))$, so $v(\binom{m}{n}) = r - v(n)$. As $r = v(m)$, this proves the desired formula. □

Lemma 1 is sharp in that the hypothesis $n \le 2^{v(m)}$ cannot be replaced with the weaker hypothesis $v(n) \le v(m)$. For example, $v(\binom{10}{6}) = v(210) = 1$, but $v(10) - v(6) = 0$.

Lemma 2 *A binomial coefficient $\binom{2m-1}{m-1}$ is odd if and only if $m = 2^r$ for some $r \ge 0$.*

Proof **Kummer's theorem** [13] (see [20, p. 78] or [24]) for the prime 2 states that $v(\binom{a+b}{a})$ equals the number of carries when adding a and b in base 2 arithmetic. Hence, $v(\binom{m+m}{m})$ is the number of ones in the binary expansion of m, and so $v(\binom{2m}{m}) = 1$ if and only if $m = 2^r$ for some $r \ge 0$. As $\binom{2m}{m} = 2\binom{2m-1}{m-1}$ by (12), we are done. □

We can now prove the converse of Babbage's non-primality test for even numbers.

Proof (Theorem 5) For $m \geq 2$ not a power of 2, Lemma 2 implies that $\binom{2m-1}{m-1}$ is even, so $\binom{2m-1}{m-1}$ is congruent modulo 4 to either 0 or 2. For $m \geq 2$ a power of 2, say $m = 2^r$, the equalities in (3) and the symmetry $\binom{m}{n} = \binom{m}{m-n}$ yield

$$\binom{2m-1}{m-1} = 1 + \frac{1}{2}\binom{2^r}{2^{r-1}}^2 + \sum_{k=1}^{2^{r-1}-1} \binom{2^r}{k}^2,$$

and Lemma 1 implies that $\frac{1}{2}\binom{2^r}{2^{r-1}}^2 \equiv 2 \pmod 4$ and that $\binom{2^r}{k}^2 \equiv 0 \pmod 4$ when $0 < k < 2^{r-1}$; thus, by addition $\binom{2m-1}{m-1} \equiv 3 \pmod 4$. Hence for all $m \geq 2$, we have $\binom{2m-1}{m-1} \not\equiv 1 \pmod 4$. Now as 4 divides m^2 when m is even, (10) holds a fortiori. This completes the proof. □

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