

# Pacific Journal of Mathematics

**TESTS FOR PRIMALITY BASED ON SYLVESTER'S  
CYCLOTOMIC NUMBERS**

MORGAN WARD

# TESTS FOR PRIMALITY BASED ON SYLVESTERS CYCLOTOMIC NUMBERS

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**Introduction.** Lucas, Carmichael [1] and others have given tests for primality of the Fermat and Mersenne numbers which utilize divisibility properties of the Lucas sequences ( $U$ ) and ( $V$ ); in this paper we are concerned only with the first sequence;

$$(U): U_0, U_1, U_2, \dots, U_n = \frac{\alpha^n - \beta^n}{\alpha - \beta}, \dots$$

Here  $\alpha$  and  $\beta$  are the roots of a suitably chosen quadratic polynomial  $x^2 - Px + Q$ , with  $P$  and  $Q$  coprime integers. (For an account of these tests, generalizations and references to the early literature, see Lehmer's Thesis [2]).

I develop here a test for primality of a less restrictive nature which utilizes a divisibility property of the Sylvester cyclotomic sequence [3]:

$$(Q): Q_0 = 0, Q_1 = 1, Q_2, \dots, Q_n = \prod_{\substack{1 \leq r \leq n \\ (r, n) = 1}} (\alpha - e^{\frac{2\pi ir}{n}} \beta), \dots$$

Here  $\alpha$  and  $\beta$  have the same meaning as before. ( $U$ ) and ( $Q$ ) are closely connected [4]; in fact

$$(1.1) \quad U_n = \prod_{d|n} Q_d.$$

The divisibility property is expressed by the following theorem proved in § 3 of this paper.

**THEOREM.** *If  $m$  is an odd number dividing some cyclotomic number  $Q_n$  whose index  $n$  is prime to  $m$ , then every divisor of  $m$  greater than one has the same rank of apparition  $n$  in the Lucas sequence ( $U$ ) connected with ( $Q$ ).*

Here the rank of apparition or rank, of any number  $d$  in ( $U$ ) means as usual the least positive index  $x$  such that  $U_x \equiv 0 \pmod{d}$ .

The following primality test is an immediate corollary.

*Primality test.* *If  $m$  is odd, greater than two, and divides some cyclotomic number  $Q_n$  whose index  $n$  is both prime to  $m$  and greater than the square root of  $m$ , then  $m$  is a prime number except in two trivial cases:  $m = (n - 1)^2$ ,  $n - 1$  a prime greater than 3, or  $m = n^2 - 1$  with  $n - 1$  and  $n + 1$  both primes.*

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The primality tests of Lucas and Carmichael are the special case when  $n = m \pm 1$  is a power of two (which allows  $Q_n$  to be expressed in terms of  $V_n$ ) with  $X^2 - Px + Q$  suitably specialized.

2. **Notations.** We denote the rational field by  $R$ , and the ring of rational integers by  $I$ . The polynomial

$$(2.1) \quad f(x) = x^2 - Px + Q, \quad P, Q, \text{ in } I \text{ and co-prime}$$

is assumed to have distinct roots  $\alpha$  and  $\beta$ .

We denote the root field of  $f(x)$  by  $\mathcal{A}$  and the ring of its integers by  $\mathcal{S}$ . Thus  $\mathcal{A}$  is either  $R$  itself, or a simple quadratic extension of  $R$ .

Let  $p$  be an odd prime of  $I$ , and  $\mathfrak{p}$  a prime ideal factor of  $p$  in  $\mathcal{S}$ . Every element  $\rho$  of  $\mathcal{A}$  may be put in the form  $\rho = \alpha/a$  with  $\alpha$  in  $\mathcal{S}$  and  $a$  in  $I$ . The totality of such  $\rho$  with  $(a, p) = 1$  forms a subring  $\mathcal{S}_p$  of  $\mathcal{A}$ . Evidently  $\mathcal{A} \supset \mathcal{S}_p \supset \mathcal{S} \supseteq I$ . If we extend  $\mathfrak{p}$  into  $\mathcal{S}_p$  in the obvious way, we obtain a prime ideal  $\mathfrak{P}$ . The homomorphic image of  $\mathcal{S}_p$  modulo  $\mathfrak{P}$  is a field,  $\mathcal{F}_p$ . We denote the mapping of  $\mathcal{S}_p$  onto  $\mathcal{F}_p$  by  $(\mathfrak{P})$ .

Let  $F_n(z)$  denote the cyclotomic polynomial of degree  $\phi(n)$ .  $F_n(z)$  has coefficients in  $I$ , and if  $n$  is greater than one, then (Lehmer [2], Carmichael [1])

$$(2.2) \quad Q_n = \beta^{\phi(n)} F_n\left(\frac{\alpha}{\beta}\right),$$

Furthermore

$$(2.3) \quad z^n - 1 = \prod_{a|n} F_n(z).$$

3. **Proof of theorem.** Let  $m$  be an odd number greater than one which divides some term of (Q) whose index  $n$  is prime to  $m$ , so that

$$(3.1) \quad Q_n \equiv 0 \pmod{m}, \quad (n, m) = 1.$$

Throughout the next three lemmas,  $p$  stands for a fixed prime factor of  $m$ .

LEMMA 1. *If  $\mathfrak{p}$  is any ideal factor of  $p$  in  $\mathcal{S}$ , then*

$$(3.2) \quad (Q, p) = (\alpha, \mathfrak{p}) = (\beta, \mathfrak{p}) = (1).$$

*Proof.* It suffices to prove that  $(Q, p) = (1)$ . Assume the contrary. Then  $(p, P) = 1$ . Since  $U_1 = 1$  and  $U_{x+2} = PU_{x+1} - QU_x \equiv PU_{x+1} \pmod{p}$ , it follows by induction that  $U_n \not\equiv 0 \pmod{p}$ . Then by (1.1),  $Q_n \not\equiv 0$

(mod  $p$ ). But  $p$  divides  $m$  so that by (3.1)  $Q_n \equiv 0 \pmod{p}$  a contradiction.

LEMMA 2. *The rank of apparition of  $p$  in  $(U)$  is  $n$ .*

*Proof.* Since  $U_n \equiv 0 \pmod{p}$ ,  $p$  has a positive rank of apparition in  $(U)$ ,  $r$  say. Then  $r$  divides  $n$ . But by (1.1),  $U_r = \prod_{a|n} Q_a$ . Hence  $Q_a \equiv 0 \pmod{p}$  for some  $d$  dividing both  $r$  and  $n$ . Clearly, if  $d = n$ , then  $r = n$  and we are finished. Assume that  $d$  is less than  $n$ .

The number  $\alpha/\beta = \alpha^2/Q$  is in  $\mathcal{S}_p$  by Lemma 1. Let  $\tau$  be its image in  $\mathcal{S}_p$  under the mapping ( $\mathfrak{A}$ ). Then by (2.2) and Lemma 1  $F_n(\tau) = F_d(\tau) = 0$  in  $\mathcal{S}_p$ . Consequently the resultant of the polynomials  $F_n(z)$  and  $F_d(z)$  is zero in  $\mathcal{S}_p$ . Therefore its inverse image under the mapping is in  $\mathfrak{A}$ . But this resultant is evidently in  $I$ . Therefore it must be divisible by  $p$ . But by formula (2.3), since  $d < n$  the resultant of  $F_n(z)$  and  $F_d(z)$  must divide the discriminant  $\pm n^{n-1}$  of  $z^n - 1$ . Thus  $n \equiv 0 \pmod{p}$  so that  $(n, m) \equiv 0 \pmod{p}$  which contradicts (3.1) and completes the proof.

LEMMA 3. *The rank of apparition in  $(U)$  of any positive power of  $p$  which divides  $m$  is  $n$ .*

*Proof.* Let  $p^k$  divide  $m$ ,  $k \geq 1$  and let the rank of  $p^k$  in  $(U)$  be  $r$ . Now  $U_n = \prod_{a|n} Q_a \equiv 0 \pmod{p^k}$ . But by Lemma 2, each  $Q_a$  with  $d < n$  is prime to  $p$ . Hence  $r$  must equal  $n$ .

The theorem proper now follows easily. For let  $m'$  be any divisor of  $m$  other than one. By Lemma 3, every prime power dividing  $m'$  has rank of apparition  $n$  in  $(U)$ . But the rank of apparition of  $m'$  in  $(U)$  is the least common multiple of the ranks of the prime powers of maximal order dividing  $m'$ . (Carmichael [1]). Hence  $m'$  also has rank of apparition  $n$  in  $(U)$ .

**4. Proof of primality test.** Assume that (3.1) holds for some  $n$  greater than  $\sqrt{m}$ . If  $m$  is not a prime, it has a prime factor  $\leq \sqrt{m}$ . Let  $p$  be the smallest such factor, and let

$$(4.1) \quad m = pq, \quad q \geq 3.$$

Then  $p$  has rank  $n$  in  $(U)$  by Lemma 3. But by a classical result of Lucas,  $U_{p \pm 1} \equiv 0 \pmod{p}$ . Hence  $n$  divides  $p \pm 1$ . If  $n$  is less than  $p + 1$ ,  $\sqrt{m} < p \leq \sqrt{m}$ , a contradiction. Hence  $n = p + 1$ . If  $p = \sqrt{m}$ , then  $m = (n - 1)^2$  and  $n - 1$  is a prime. Since  $m$  is odd,  $n \geq 4$ . This is the first trivial case.

If  $p < \sqrt{m}$ , then  $q \geq p + 2$  and  $m \geq p(p + 2)$ . But if  $m > p(p + 2)$ ,

then  $n^2 > m \geq (p + 1)^2 = n^2$ , a contradiction. Hence  $m = p(p + 2)$  where  $p + 2$  has no prime factor smaller than  $p$ . Hence  $p + 2$  is a prime and  $m = n^2 - 1$  with both  $n - 1$  and  $n + 1$  primes. This is the second trivial case. In every other case then,  $m$  must be a prime.

**5. Conclusion.** The two trivial cases can actually occur. For if  $P = 22$  and  $Q = 3$ , then  $Q_6 = \alpha^2 - \alpha\beta + \beta^2 = P^2 - 3Q = 475$ . Hence  $Q_6 \equiv 0 \pmod{25}$  and  $25 = (6 - 1)^2$ . Again, if  $P = 17$  and  $Q = 3$ , then  $Q_6 = 280$ . Hence  $Q_6 \equiv 0 \pmod{35}$  and  $35 = 6^2 - 1 = 5 \times 7$ . It is worth noting that these trivial cases cannot occur if  $\alpha$  and  $\beta$  are rational integers. (See [1], Theorem XII and remark.)

To illustrate the theorem, note that if  $P = 2$  and  $Q = 1$ ,  $Q_9 = 73$ . Since  $\sqrt{73} < 9$  and  $(9, 73) = 1$ , 73 is a prime. But for  $P = 3$  and  $Q = 1$ ,  $Q_9 = 91$ . But  $9 < \sqrt{91}$  so the test is inapplicable. As a matter of fact, 91 is the product of two primes. Evidently the test may be extended to cover such a case. That is, if  $Q_n \equiv 0 \pmod{m}$ ,  $(n, m) = 1$  and  $n > \sqrt[3]{m}$ ,  $m$  will usually be either a prime, or the product of two primes.

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