Cantor Primes as Prime-Valued Cyclotomic Polynomials

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Abstract

Cantor primes are primes $p$ such that $1/p$ belongs to the middle-third Cantor set. One way to look at them is as containing the base-3 analogues of the famous Mersenne primes, which encompass all base-2 repunit primes, i.e., primes consisting of a contiguous sequence of 1’s in base 2 and satisfying an equation of the form $p + 1 = 2^q$. The Cantor primes encompass all base-3 repunit primes satisfying an equation of the form $2p + 1 = 3^q$, and I show that in general all Cantor primes $> 3$ satisfy a closely related equation of the form $2pK + 1 = 3^q$, with the base-3 repunits being the special case $K = 1$. I use this to prove that the Cantor primes $> 3$ are exactly the prime-valued cyclotomic polynomials of the form $\Phi_s(3^q) \equiv 1 \pmod{4}$. Significant open problems concern the infinitude of these, making Cantor primes perhaps more interesting than previously realised.

Keywords: Cantor set, prime numbers, cyclotomic polynomials

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1 Introduction

Any base-$N$ repunit prime $p$ is a cyclotomic polynomial evaluated at $N$, $\Phi_q(N)$, with $q$ also prime, i.e.,

$$p = \Phi_q(N) = \frac{N^q - 1}{N - 1} = \sum_{k=0}^{q-1} N^k$$

(1)

It is therefore expressible as a contiguous sequence of 1’s in base $N$. For example, $p = 31$ satisfies (1) for $N = 2$ and $q = 5$ and can be expressed as
The term repunit was coined by A. H. Beiler [1] to indicate that numbers like these consist of repeated units.

The case \( N = 2 \) corresponds to the famous Mersenne primes on which there is a vast literature [6]. They are sequence number A000668 in The Online Encyclopedia of Integer Sequences [7] and are exactly the prime-valued cyclotomic polynomials of the form \( \Phi_s(2) \equiv 3 \pmod{4} \).

In this note I show that Cantor primes can be characterised in a similar way as being exactly the prime-valued cyclotomic polynomials of the form \( \Phi_s(3^r) \equiv 1 \pmod{4} \). They are primes whose reciprocals belong to the middle-third Cantor set \( C_3 \).

It is easily shown that \( C_3 \) contains the reciprocals of all base-3 repunit primes, i.e., those primes \( p \) which satisfy an equation of the form \( 2p + 1 = 3^q \) with \( q \) prime. \( C_3 \) is a fractal consisting of all the points in \([0, 1]\) which have non-terminating base-3 representations involving only the digits 0 and 2. Rerranging (1) to get the infinite series

\[
\frac{1}{p} = \frac{N - 1}{N^q - 1} = \sum_{k=1}^{\infty} \frac{N - 1}{N^{q^k}}
\]

and putting \( N = 3 \) shows that those primes \( p \) which satisfy \( 2p + 1 = 3^q \) are such that \( \frac{1}{p} \) can be expressed in base 3 using only zeros and the digit 2. This single digit 2 will appear periodically in the base-3 representation of \( \frac{1}{p} \) at positions which are multiples of \( q \). Since only zeros and the digit 2 appear in the ternary representation of \( \frac{1}{p} \), \( \frac{1}{p} \) is never removed in the construction of \( C_3 \), so \( \frac{1}{p} \) must belong to \( C_3 \).

Base-3 repunit primes are sequence number A076481 in The Online Encyclopedia of Integer Sequences and the exact analogues of the Mersenne primes, i.e., they are the case \( N = 3 \) in (1). In the next section I show that Cantor primes \( > 3 \) more generally satisfy a closely related equation of the form \( 2pK + 1 = 3^q \), with the base-3 repunits being the special case \( K = 1 \). A subsequent section proves that the Cantor primes \( > 3 \) are exactly the prime-valued cyclotomic polynomials of the form \( \Phi_s(3^r) \equiv 1 \pmod{4} \), and a final section considers related open problems.

## 2 An Exponential Equation Characterising All Cantor Primes

**Theorem 2.1.** A prime number \( p > 3 \) is a Cantor prime if and only if it satisfies an equation of the form \( 2pK + 1 = 3^q \) where \( q \) is the order of 3 modulo \( p \) and \( K \) is a sum of non-negative powers of 3 each smaller than \( 3^q \).
Comment. The base-3 repunit primes are then the special case in which $K = 3^0 = 1$. An example is 13, which satisfies $2p + 1 = 3^3$. A counterexample which shows that not all Cantor primes are base-3 repunit primes is 757, which satisfies $26p + 1 = 3^6$ with $K = 3^6 + 3^4 + 3^2 = 13$ and $q = 9$.

Proof. Each $x \in C_3$ can be expressed in ternary form as

$$x = \sum_{k=1}^{\infty} \frac{a_k}{3^k} = 0.a_1a_2 \ldots$$

where all the $a_k$ are equal to 0 or 2. The construction of $C_3$ amounts to systematically removing all the points in $[0,1]$ which cannot be expressed in ternary form with only 0’s and 2’s, i.e., the removed points all have $a_k = 1$ for one or more $k \in \mathbb{N}$ [4].

The construction of the Cantor set suggests some simple conditions which a prime number must satisfy in order to be a Cantor prime. If a prime number $p > 3$ is to be a Cantor prime, the first non-zero digit $a_{k_1}$ in the ternary expansion of $\frac{1}{p}$ must be 2. This means that for some $k_1 \in \mathbb{N}$, $p$ must satisfy

$$\frac{2}{3^{k_1}} < \frac{1}{p} < \frac{1}{3^{k_1-1}}$$

or equivalently

$$3^{k_1} \in (2p, 3p)$$

Prime numbers for which there is no power of 3 in the interval $(2p, 3p)$, e.g., 5, 7, 17, 19, 23, 41, 43, 47, ..., can therefore be excluded immediately from further consideration. Note that there cannot be any other power of 3 in the interval $(2p, 3p)$ since $3^{k_1-1}$ and $3^{k_1+1}$ lie completely to the left and completely to the right of $(2p, 3p)$ respectively.

If the next non-zero digit after $a_{k_1}$ is to be another 2 rather than a 1, it must be the case for some $k_2 \in \mathbb{N}$ that

$$\frac{2}{3^{k_1+k_2}} < \frac{1}{p} - \frac{2}{3^{k_1}} < \frac{1}{3^{k_1+k_2-1}}$$

or equivalently

$$3^{k_2} \in \left(\frac{2p}{3^{k_1} - 2p}, \frac{3p}{3^{k_1} - 2p}\right)$$

Thus, any prime numbers for which there is a power of 3 in the interval $(2p, 3p)$ but for which there is no power of 3 in the interval $(\frac{2p}{3^{k_1} - 2p}, \frac{3p}{3^{k_1} - 2p})$ can again be excluded, e.g., 37, 113, 331, 337, 353, 991, 997, 1009.

Continuing in this way, the condition for the third non-zero digit to be a 2 is

$$3^{k_3} \in \left(\frac{2p}{3^{k_2}(3^{k_1} - 2p) - 2p}, \frac{3p}{3^{k_2}(3^{k_1} - 2p) - 2p}\right)$$
and the condition for the $n$th non-zero digit to be a 2 is

$$3^{k_n} \in \left( \frac{2p}{3^{k_{n-1}}(\cdots (3^{k_2}(3^{k_1} - 2p) - 2p) \cdots) - 2p}, \frac{3p}{3^{k_{n-1}}(\cdots (3^{k_2}(3^{k_1} - 2p) - 2p) \cdots) - 2p} \right)$$

(9)

The ternary expansions under consideration are all non-terminating, so at first sight it seems as if an endless sequence of tests like these would have to be applied to ensure that $a_k \neq 1$ for any $k \in \mathbb{N}$. However, this is not the case. Let $p$ be a Cantor prime and let $3^{k_1}$ be the smallest power of 3 that exceeds $2p$. Since $p$ is a Cantor prime, both (5) and (9) must be satisfied for all $n$. Multiplying (9) through by $3^{k_1 - k_n}$ we get

$$3^{k_1} \in \left( \frac{3^{k_1 - k_n} \cdot 2p}{3^{k_{n-1}}(\cdots (3^{k_2}(3^{k_1} - 2p) - 2p) \cdots) - 2p}, \frac{3^{k_1 - k_n} \cdot 3p}{3^{k_{n-1}}(\cdots (3^{k_2}(3^{k_1} - 2p) - 2p) \cdots) - 2p} \right)$$

(10)

Since all ternary representations of prime reciprocals $\frac{1}{p}$ for $p > 3$ have a repeating cycle which begins immediately after the point, it must be the case that $k_n = k_1$ for some $n$ in (10). Setting $k_n = k_1$ in (10) we can therefore deduce from the fact that $3^{k_1} \in (2p, 3p)$ and the fact that (10) must be consistent with this for all values of $n$, that all Cantor primes must satisfy an equation of the form

$$3^{k_{n-1}}(\cdots (3^{k_2}(3^{k_1} - 2p) - 2p) \cdots) - 2p = 1$$

(11)

where $k_1 + k_2 + \cdots + k_{n-1} = q$ is the cycle length in the ternary representation of $\frac{1}{p}$. In other words, $q$ is the order of 3 modulo $p$. By successively considering the cases in which there is only one non-zero term in the repeating cycle, two non-zero terms, three non-zero terms, etc., in (11), and defining

$$d_1 = q - k_1$$
$$d_2 = q - k_1 - k_2$$
$$d_3 = q - k_1 - k_2 - k_3$$
$$\vdots$$
$$d_n = q - k_1 - k_2 - \cdots - k_n = 0$$

it is easy to see that (11) can be rearranged as

$$2p \sum_{i=1}^{n} 3^{d_i} + 1 = 3^q$$

(12)

Setting $K = \sum_{i=1}^{n} 3^{d_i}$, we conclude that every Cantor prime must satisfy an equation of the form $2pK + 1 = 3^q$ as claimed.
Conversely, every prime which satisfies an equation of this form must be a Cantor prime. To see this, note that we can rearrange (12) to get

\[
\frac{1}{p} = 2 \sum_{i=1}^{n} \frac{3^{d_i}}{3^q - 1} = 2 \sum_{i=1}^{n} 3^{d_i} \left\{ \frac{1}{3^q} + \frac{1}{3^{2q}} + \frac{1}{3^{3q}} + \cdots \right\}
\]

Since \(2 \sum_{i=1}^{n} 3^{d_i}\) involves only products of 2 with powers of 3 which are each less than \(3^q\), (13) is an expression for \(\frac{1}{p}\) which corresponds to a ternary representation involving only 2s. Thus, \(\frac{1}{p}\) must be in the Cantor set if \(2pK + 1 = 3^q\).

### 3 Cantor Primes as Cyclotomic Polynomials

Let \(n\) be a positive integer and let \(\zeta_n\) be the complex number \(e^{2\pi i/n}\). The \(n\)th cyclotomic polynomial is defined as

\[\Phi_n(x) = \prod_{1 \leq k < n, \gcd(k,n)=1} (x - \zeta_n^k)\]

The degree of \(\Phi_n(x)\) is \(\varphi(n)\) where \(\varphi\) is the Euler totient function. There is now a powerful body of theory relating to cyclotomic polynomials and discussions of their basic properties can be found in any textbook on abstract algebra.

**Lemma 3.1.** \(x^{(n-1)a} + x^{(n-2)a} + \cdots + x^{2a} + x^a + 1\) is irreducible in \(\mathbb{Z}[x]\) if and only if \(n = p\) and \(a = p^k\) for some prime \(p\) and non-negative integer \(k\).

**Proof.** This is proved as Theorem 4 in [5].

**Theorem 3.2.** A prime number \(p > 3\) is a Cantor prime if and only if \(p = \Phi_{s}(3^j) \equiv 1 \pmod{4}\) where \(s\) is an odd prime and \(j\) is a non-negative integer.

**Proof.** Assume \(p\) is a Cantor prime. By Theorem 2.1 we then have

\[pK = \frac{3^q - 1}{2} = R_q^{(3)}\]

where \(R_q^{(3)}\) denotes the base-3 repunit consisting of \(q\) contiguous units, and \(q\) and \(K\) are as defined in that theorem. If \(q\) is composite, say \(q = rs\), we obtain the factorisation

\[R_q^{(3)} = R_r^{(3)} \cdot (3^{(s-1)r} + 3^{(s-2)r} + \cdots + 3^{2r} + 3^{r} + 1)\]

If \(q\) is prime we can take \(r = 1\). Therefore in both cases at least one factor of \(pK\) must be a base-3 repunit.
If \( K = 1 \) then \( p = R_q^{(3)} = \Phi_s(3) \), since \( q \) must be prime in this case. \((R_q^{(3)} \) is composite if \( q \) is). If \( K > 1 \), \( p \) is not a base-3 repunit and by Theorem 2.1 \( K \) is a sum of powers of 3, so \( p \) must be of the general form
\[
p = 3^{(s-1)r} + 3^{(s-2)r} + \cdots + 3^{2r} + 3^r + 1 \tag{16}
\]
for some \( s \) and \( r \), and \( K \) must be a corresponding base-3 repunit \( R_r^{(3)} \), otherwise their product could not be \( R_r^{(3)} \). But the polynomial in (16) can only be prime if it is irreducible in \( \mathbb{Z}[x] \). By Lemma 3.1, this requires \( s \) to be a prime number and \( r = s^j \) for some non-negative integer \( j \), and we therefore have \( p = \Phi_s(3^{s^j}) \) in this case. We conclude that in all cases we must have \( p = \Phi_s(3^{s^j}) \) if \( p \) is a Cantor prime. Note that \( s \) must be an odd prime as \( \Phi_s(3^{s^j}) \) is even for \( s = 2 \).

Conversely, suppose that \( p = \Phi_s(3^{s^j}) \) is a prime number. Then we can multiply it by the base-3 repunit \( R_r^{(3)} \) where \( r = s^j \) to get the repunit \( R_q^{(3)} \) as in (15). Thus, \( p \) must satisfy (14) and must therefore be a Cantor prime.

Base-3 repunits are congruent to 0 modulo 4 when they consist of an even number of digits, and to 1 modulo 4 otherwise. Therefore if \( p > 3 \) is a base-3 repunit prime it must be of the form \( 4k + 1 \).

If \( p \) is prime but not a base-3 repunit, both \( r = s^j \) and \( q = rs \) in (15) are odd, so both \( R_q^{(3)} \) and \( R_r^{(3)} \) are base-3 repunits with odd numbers of digits, and thus of the form \( 4k + 1 \). It follows that \( p \) is also of the form \( 4k + 1 \) in this case.

### 4 Open Problems

The infinitude of Cantor primes is currently an open problem shown to be significant in this paper because of the equivalence of Cantor primes and prime-valued cyclotomic polynomials of the form \( \Phi_s(3^{s^j}) \).

In the case \( j = 0 \), it is known that \( \Phi_s(3) \) is prime for \( s = 7, 13, 71, 103, 541, 1091, 1367, 1627, 4177, 9011, 9551, 36913, 43063, 49681, 57917, 483611, \) and \( 877843 \). It seems plausible that there are infinitely many such values of \( s \) but this remains to be proved.

The Cantor prime \( 757 = \Phi_3(3^3) \) is an example with \( j > 0 \). It is again an open problem to prove there are infinitely many integers \( j > 0 \) for which \( \Phi_s(3^{s^j}) \) is prime given a prime \( s \), though all such cyclotomic polynomials must be irreducible.

Previous studies have considered the infinitude of prime-valued cyclotomic polynomials of other types. For example, primes of the form \( \Phi_s(1) \) and \( \Phi_s(2) \) are studied in [3], and other cases are discussed in [2].

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References


