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ON THE p-ADIC ZEROS OF THE TRIBONACCI SEQUENCE

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ABSTRACT. Let $(T_n)_{n\in\mathbb{Z}}$ be the Tribonacci sequence and for a prime p and an integer m let $\nu_p(m)$ be the exponent of p in the factorization of m. For $p = 2$ Marques and Lengyel found some formulas relating $\nu_p(T_n)$ with $\nu_p(f(n))$ where $f(n)$ is some linear function of n (which might be constant) according to the residue class of n modulo 32 and asked if similar formulas exist for other primes p. In this paper, we give an algorithm which tests whether for a given prime p such formulas exist or not. When they exist, our algorithm computes these formulas. Some numerical results are presented.

1. INTRODUCTION

Let $\Lambda = \{\lambda_1, \lambda_2, \lambda_3\} \subset \overline{\mathbb{Q}}$ be the set of roots of the polynomial

$$P(X) = X^3 - X^2 - X - 1.$$

For $\lambda \in \Lambda$ define $c_\lambda = \lambda P'(\lambda)^{-1}$. For $n \in \mathbb{Z}$, the *Tribonacci number* $T(n) \in \mathbb{Z}$ is defined by

$$T(n) = \sum_{\lambda\in\Lambda} c_\lambda \lambda^n.$$

More famously, $T : \mathbb{Z} \to \mathbb{Z}$ is defined by the recurrence relation

$$\begin{aligned} &T(0) = 0, \qquad T(1) = T(2) = 1, \\ &T(n+3) = T(n+2) + T(n+1) + T(n) \qquad (n \in \mathbb{Z}). \end{aligned}$$

Attention: $a(n)$ in [8] corresponds to our $T(n+1)$.

It is known that $T(n) = 0$ if and only if $n \in \mathcal{Z}_T := \{0, -1, -4, -17\}$. For a proof see, for instance, [10, Example 2 on page 360]; in that example u_n corresponds to our $T(-n)$. In [9], Marques and Lengyel determined the exponent of 2 in T_n. Denoting for a prime p and a non-zero integer m by $\nu_p(m)$ the exact exponent of p in the factorization of m, and setting $\nu_p(0) = \infty$, they proved Theorem 1.1.

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Theorem 1.1. *For $n \geq 1$, we have*

$$\nu_2(T_n) = \begin{cases} 0, & \text{if } n \equiv 1,2 \pmod 4; \\ 1, & \text{if } n \equiv 3,11 \pmod{16}; \\ 2, & \text{if } n \equiv 4,8 \pmod{16}; \\ 3, & \text{if } n \equiv 7 \pmod{16}; \\ \nu_2(n)-1, & \text{if } n \equiv 0 \pmod{16}; \\ \nu_2(n+4)-1, & \text{if } n \equiv 12 \pmod{16}; \\ \nu_2(n+17)+1, & \text{if } n \equiv 15 \pmod{32}; \\ \nu_2(n+1)+1, & \text{if } n \equiv 31 \pmod{32}. \end{cases}$$

Encouraged by their result for the prime $p = 2$, they conjectured that such formulas should hold for $\nu_p(T_n)$ for every prime p. More precisely, here is their conjecture.

Conjecture 1.2 (Conjecture 8 from [9])**.** *Let p be a prime number. There exists a positive integer Q such that for every $i \in \{0, 1, \dots, Q-1\}$ we have one of the following two options.*

(C) *There exists $\kappa_i \in \mathbb{Z}_{\geq 0}$ such that for all but finitely many $n \in \mathbb{Z}$ satisfying $n \equiv i \pmod Q$ we have $\nu_p(T(n)) = \kappa_i$.*

(L) *There exist*

$$a_i \in \mathbb{Z}, \qquad \kappa_i \in \mathbb{Z}, \qquad \mu_i \in \mathbb{Z}_{>0}$$

satisfying

$$\nu_p(a_i - i) \geq \nu_p(Q), \tag{1.1}$$

such that for all but finitely many $n \in \mathbb{Z}$ satisfying $n \equiv i \pmod Q$ we have

$$\nu_p(T(n)) = \kappa_i + \mu_i \nu_p(n - a_i). \tag{1.2}$$

Note that our statement looks different from Conjecture 8 from [9], but, in fact, it is equivalent to it.

Informally, in the case (C) (that is, "constant") $\nu_p(T(n))$ is a constant function on the entire residue class $n \equiv i \pmod Q$ with finitely many n removed, while in the case (L) ("linear") it is a linear function of $\nu_p(n - a_i)$.

Remark 1.3. Let us comment on condition (1.1), which does not appear in [9]. This condition is needed to ensure that the right-hand side of (1.2) is not constant (in which case option (C) would hold for the class $n \equiv i \pmod Q$). To be precise, the following three statements are equivalent:

(1) (1.1) holds;
(2) $\nu_p(n - a_i)$ is not constant on the residue class $n \equiv i \pmod Q$;
(3) $\nu_p(n - a_i)$ is not bounded on the residue class $n \equiv i \pmod Q$.

Indeed, if $\nu_p(a_i - i) < \nu_p(Q)$ then $\nu_p(n - a_i) = \nu_p(i - a_i)$ for $n \equiv i \pmod Q$, which proves the implication (2).⇒(1). The implication (3).⇒(2). is obvious. Finally, assume that (1.1) holds. Denoting $\nu := \nu_p(Q)$, for every $k \geq \nu$ the Chinese remainder theorem provides $m_k \in \mathbb{Z}$ satisfying

$$m_k \equiv \frac{a_i - i}{p^\nu} \pmod{p^{k-\nu}}, \qquad m_k \equiv 0 \pmod{Qp^{-\nu}}.$$

Then $n_k := i + m_k p^\nu$ satisfies $n_k \equiv a_i \pmod{p^k}$ and $n_k \equiv i \pmod Q$, which proves the implication (1).⇒(3).

Already the case $p = 3$ looks encouraging.

Theorem 1.4. *For $n \geq 1$, we have*

$$\nu_3(T_n) = \begin{cases} 0, & \text{if } n \equiv 1,2,3,4,5,6,8,10,11 \pmod{13}; \\ 1, & \text{if } n \equiv 7 \pmod{13}; \\ \nu_3(n)+2, & \text{if } n \equiv 0 \pmod{13}; \\ \nu_3(n+1)+2, & \text{if } n \equiv 12 \pmod{13}; \\ 4, & \text{if } n \equiv 9 \pmod{39}; \\ \nu_3(n+17)+4, & \text{if } n \equiv 22 \pmod{39}; \\ \nu_3(n+4)+4, & \text{if } n \equiv 35 \pmod{39}. \end{cases}$$

However, Theorem 1.5 shows that Conjecture 1.2 fails for infinitely many primes.

Theorem 1.5. *There is an infinite set*[1] *of prime numbers congruent to* 2 (mod 3) *such that for every prime p from this set the following hold.*

(1) *For each $n \in \mathbb{Z}$ satisfying $n \equiv 1/3 \pmod{p-1}$ we have*
$$\nu_p(T(n)) \geq \nu_p(n - 1/3).$$

(2) *For each $n \in \mathbb{Z}$ with $n \equiv -5/3 \pmod{p-1}$ we have*
$$\nu_p(T(n)) \geq \nu_p(n + 5/3).$$

Clearly, Theorem 1.5 contradicts Conjecture 1.2. Indeed, let p be as in the theorem, and let (n_k) be a sequence of integers satisfying

$$n_k \equiv 1/3 \pmod{(p-1)p^k}.$$

If Conjecture 1.2 is true for this p then for some $i \in \{0, \dots, Q-1\}$ the residue class $i \pmod{Q}$ contains infinitely many n_k. Since $\nu_p(n_k - 1/3) \to \infty$, we have $\nu_p(T(n)) \to \infty$. Hence for this i we must have option (L) of Conjecture 1.2:

$$\nu_p(T(n_k)) = \kappa_i + \mu_i \nu_p(n_k - a_i).$$

Moreover, we must have $\nu_p(n_k - a_i) \to \infty$ as well. But, since $a_i \in \mathbb{Z}$, we have $a_i \neq 1/3$, and hence $\nu_p(n_k - 1/3)$ and $\nu_p(n_k - a_i)$ cannot both tend to infinity.

One may hope to rescue Conjecture 1.2 by allowing a_i to be rational numbers, as below:

Conjecture 1.6. *Let p be a prime number. There exists a positive integer Q such that for every $i \in \{0, 1, \dots, Q-1\}$ we have one of the following two options.*

(C) *There exists $\kappa_i \in \mathbb{Z}_{\geq 0}$ such that for all but finitely many $n \in \mathbb{Z}$ satisfying $n \equiv i \pmod{Q}$ we have $\nu_p(T(n)) = \kappa_i$.*

(L) *There exist*
$$a_i \in \mathbb{Q}, \qquad \kappa_i \in \mathbb{Z}, \qquad \mu_i \in \mathbb{Z}_{>0}$$
satisfying $\nu_p(a_i - i) \geq \nu_p(Q)$, such that for all but finitely many $n \in \mathbb{Z}$ satisfying $n \equiv i \pmod{Q}$ we have $\nu_p(T(n)) = \kappa_i + \mu_i \nu_p(n - a_i)$.

However we show that even this weaker conjecture fails for many primes. In fact we provide a method to decide for which primes p Conjectures 1.2 and 1.6 hold and for which they fail. In some cases our method is unable to make the desired decision. When the method works and decides that the conjecture holds, it also determines the parameters Q and (a_i, μ_i) for those $i = \{0, \dots, Q-1\}$ for which option (L) takes place.

Concerning Conjecture 1.2, we have:

[1] We will see that this set of primes is not only infinite, but is of relative density 1/12 in the set of all primes.

Theorem 1.7.

(i) *Conjecture* 1.2 *fails for* $p \in [5,599]\backslash\{11,83,103,163,397\}$.

(ii) *Conjecture* 1.2 *holds for* $p \in \{83,397\}$ *in the form*

$$\nu_p(T_n) = \begin{cases} \nu_p(n+c)+1, & \text{if} \quad n \equiv -c \pmod{Q_p},\ -c \in \mathcal{Z}_T; \\ 0, & \text{otherwise,} \end{cases}$$

with $Q_{83} = 287$ *and* $Q_{397} = 132$.

Note that our method does not handle the prime $p = 11$. As for the cases $p \in \{103,163\}$, our method failed to decide whether Conjecture 1.2 holds.

Concerning Conjecture 1.6, we have:

Theorem 1.8.

(i) *Conjecture* 1.6 *fails for*

$$p \in [5,599]\backslash\{11,47,53,83,103,163,269,397,401,419,499,587\}.$$

(ii) *Conjecture* 1.6 *holds for* $p \in \{269,401,419,499,587\}$ *in the form*

$$\nu_p(T_n) = \begin{cases} \nu_p(n+c)+1, & \text{if} \quad n \equiv c \pmod{Q_p}, \\ & \quad c \in \{0,-1,-4,-17,1/3,-5/3\}; \\ 0, & \text{otherwise,} \end{cases}$$

with $Q_{269} = 268$, $Q_{401} = 400$, $Q_{419} = 418$, $Q_{499} = 166$ *and* $Q_{587} = 293$.

Note here that (again) our method does not apply to the prime $p = 11$. As for $p \in \{47,53,103,163\}$, our method failed to decide whether Conjecture 1.6 holds.

Plan of the article. In Section 2 we introduce the basic notions of this article, those of twisted zeros and of rational zeros of the Tribonacci sequence.

In Section 3 we recall the necessary tools from p-adic analysis. In Sections 4–8 we apply these tools to study the Tribonacci sequence. In particular, Theorem 1.5 is proved in Section 5. In Section 6 we give a p-adic analytic interpretation of Conjectures 1.2 and 1.6. Using it, we produce in Section 8 easily verifiable sufficient conditions for both conjectures to hold and to fail.

Theorems 1.4 and 1.7 are proved in Section 9, as application of the previous results together with some computations.

The final Section 10 contains heuristics which suggest that if $\mathcal{ML}$ and $\mathcal{NMLR}$ are the sets of all primes such that Conjecture 1.2 holds and Conjecture 1.6 fails, respectively, then both $\mathcal{ML}$ and $\mathcal{NMLR}$ are infinite and maybe even of positive relative densities as subsets of all primes.

A convention. Unless otherwise stated, all congruences such as $x \equiv y \pmod{N}$ and divisibility relations such as $x \mid y$ refer to the ring of rational integers $\mathbb{Z}$.

We slightly abuse notation by writing $x \equiv y \pmod{N}$ with $x, y \in \mathbb{Q}$ if there exists $m \in \mathbb{Z}$ with $\gcd(m,N) = 1$ such that $mx, my \in \mathbb{Z}$ and $mx \equiv my \pmod{N}$.

2. Rational zeros of the Tribonacci sequence

As we mentioned in Section 1, $T(n) = 0$ if and only if n belongs to the set $\mathcal{Z}_T = \{0,-1,-4,-17\}$. It turns out that, in a sense, the Tribonacci sequence also "vanishes" at some non-integral rational numbers.

Proposition 2.1. *For some definition of the cubic roots*

$$\lambda^{1/3} \qquad (\lambda \in \Lambda), \tag{2.1}$$

we have

$$\sum_{\lambda\in\Lambda} c_\lambda \lambda^{1/3} = 0. \tag{2.2}$$

Similarly, for some definition of the cubic roots (2.1) *we have* $\sum_{\lambda\in\Lambda} c_\lambda \lambda^{-5/3} = 0$.

Proof. Consider the polynomial

$$F(X_1, X_2, X_3) = X_1^3 + X_2^3 + X_3^3 - 3X_1X_2X_3 \in \mathbb{Z}[X_1, X_2, X_3].$$

Write again $\Lambda = \{\lambda_1, \lambda_2, \lambda_3\}$. Define somehow the cubic roots $\lambda_1^{1/3}, \lambda_2^{1/3}$ and set $\lambda_3^{1/3} = (\lambda_1^{1/3}\lambda_2^{1/3})^{-1}$. Now define

$$\alpha_i = c_{\lambda_i}\lambda_i^{1/3}, \quad \beta_i = c_{\lambda_i}\lambda_i^{-5/3} \qquad (i = 1, 2, 3).$$

A direct verification shows that

$$F(\alpha_1, \alpha_2, \alpha_3) = \sum_{\lambda\in\Lambda} c_\lambda^3 \lambda - 3\prod_{\lambda\in\Lambda} c_\lambda = 0,$$

and, similarly, $F(\beta_1, \beta_2, \beta_3) = 0$. Since $F(X_1, X_2, X_3)$ factors as

$$F(X_1, X_2, X_3) = (X_1 + X_2 + X_3)(X_1 + \zeta X_2 + \overline{\zeta} X_3)(X_1 + \overline{\zeta} X_2 + \zeta X_3),$$

where $\zeta, \overline{\zeta}$ are the primitive cubic roots of unity, the result follows. □

Call $r \in \mathbb{Q}$ a *rational zero* of T if for some definition of the rational powers $\lambda_1^r, \lambda_2^r, \lambda_3^r$ we have $\sum_{i=1}^3 c_{\lambda_i}\lambda_i^r = 0$.

More generally, call $r \in \mathbb{Q}$ a *twisted rational zero* of T if for some definition of the rational powers $\lambda_1^r, \lambda_2^r, \lambda_3^r$ and for some roots of unity ξ_1, ξ_2, ξ_3, we have $\sum_{i=1}^3 \xi_i c_{\lambda_i}\lambda_i^r = 0$.

We denote $\mathcal{Q}_T$ the set of twisted rational zeros of T. Clearly, $\mathcal{Z}_T \subset \mathcal{Q}_T$ and $1/3, -5/3 \in \mathcal{Q}_T$. It turns out that T has no other twisted rational zeros.

Theorem 2.2. *We have*

$$\mathcal{Q}_T = \mathcal{Z}_T \cup \{1/3, -5/3\} = \{0, -1, -4, -17, 1/3, -5/3\}.$$

Moreover, if $r \in \mathcal{Q}_T$ and the powers $\lambda_1^r, \lambda_2^r, \lambda_3^r$ are suitably defined, then for the roots of unity ξ_1, ξ_2, ξ_3 satisfying $\sum_{i=1}^3 \xi_i c_{\lambda_i}\lambda_i^r = 0$ we have $\xi_1 = \xi_2 = \xi_3$.

The full proof of Theorem 2.2 will appear in [1]. In this paper we prove only a weaker version of this theorem, addressing twisted integral zeros.

Theorem 2.3. *Let $n \in \mathbb{Z}$ and ξ_1, ξ_2, ξ_3 roots of unity such that $\sum_{i=1}^3 \xi_i c_{\lambda_i}\lambda_i^n = 0$. Then $n \in \mathcal{Z}_T$ and $\xi_1 = \xi_2 = \xi_3 = 1$. In particular, the only twisted integral zeros of the Tribonacci sequence are its actual zeros $0, -1, -4, -17$.*

Remark 2.4. Of course, twisted zeros can be defined for any linear recurrent sequence, not just of the Tribonacci sequence: if $U(n)$ is a linear recurrence with Binet expansion

$$U(n) = P_1(n)\gamma_1^n + \cdots + P_s(n)\gamma_s^n$$

(where $\gamma_1, \ldots, \gamma_s$ are non-zero algebraic numbers and $P_1, \ldots, P_s$ are polynomials with algebraic coefficients), then we call $r \in \mathbb{Q}$ a twisted rational zero of U if for some definition of the powers $\gamma_1^r, \ldots, \gamma_s^r$ and some roots of unity $\xi_1, \ldots, \xi_s$ we have $\xi_1 P_1(r)\gamma_1^r + \cdots + \xi_s P_s(r)\gamma_s^r = 0$. Note that the analogue of Theorem 2.3 does not hold for any linear recurrent sequence. For instance, the binary sequence

$U(n) = 2^n + 1^n$ has no integral zeros, but it has a twisted zero at $n = 0$, the relevant roots of unity being 1 and -1:

$$1 \cdot 2^0 + (-1) \cdot 1^0 = 0.$$

For the proof of Theorem 2.3 we need some lemmas.

Lemma 2.5. *Let α be an algebraic number of degree 3. Assume that $\mathbb{Q}(\alpha)$ is not a Galois extension of $\mathbb{Q}$. Let $\alpha_1(=\alpha), \alpha_2, \alpha_3$ be the conjugates of α over $\mathbb{Q}$. Assume further that the field $\mathbb{Q}(\alpha_1, \alpha_2, \alpha_3)$ does not contain primitive cubic roots of unity.*

Let ξ_1, ξ_2, ξ_3 be roots of unity such that

$$\alpha_1\xi_1 + \alpha_2\xi_2 + \alpha_3\xi_3 = 0.$$

Then $\xi_1 = \xi_2 = \xi_3$ and hence $\alpha_1 + \alpha_2 + \alpha_3 = 0$.

Proof. We may assume that $\xi_3 = 1$, so that $\alpha_1\xi_1 + \alpha_2\xi_2 + \alpha_3 = 0$. We want to prove that $\xi_1 = \xi_2 = 1$.

Denote $\mathbb{K} = \mathbb{Q}(\alpha_1, \alpha_2, \alpha_3)$ and let $\mathbb{K}_0$ be the unique quadratic subfield of $\mathbb{K}$; note that $\mathbb{K}_0$ is the maximal abelian subfield of $\mathbb{K}$.

Assume for a contradiction that $\{\xi_1, \xi_2\} \not\subset \mathbb{K}$. Then there is a non-trivial element $\sigma \in \mathrm{Gal}(\mathbb{K}(\xi_1, \xi_2)/\mathbb{K})$. We have $\alpha_1\xi_1^\sigma + \alpha_2\xi_2^\sigma + \alpha_3 = 0$ and, without loss of generality, $\xi_1^\sigma \neq \xi_1$. It follows that $\eta := \alpha_1/\alpha_2 = -(\xi_2 - \xi_2^\sigma)/(\xi_1 - \xi_1^\sigma)$. In particular, η belongs to an abelian field and so $\eta \in \mathbb{K}_0$. But the elements of $\mathbb{K}_0$ are fixed by a cyclic permutation of $\alpha_1, \alpha_2, \alpha_3$. Hence $\eta = \alpha_1/\alpha_2 = \alpha_2/\alpha_3 = \alpha_3/\alpha_1$. It follows that $\eta^3 = (\alpha_1/\alpha_2)(\alpha_2/\alpha_3)(\alpha_3/\alpha_1) = 1$, contradicting the hypothesis that $\mathbb{K}$ contains no primitive cubic roots of unity. We conclude that ξ_1 and ξ_2 belong to $\mathbb{K}$ and hence also to $\mathbb{K}_0$.

Observe that any element of $\mathrm{Gal}(\mathbb{K}/\mathbb{Q})$ of order 2 restricts to the non-trivial element ι of $\mathrm{Gal}(\mathbb{K}_0/\mathbb{Q})$. Consider first the element of $\mathrm{Gal}(\mathbb{K}/\mathbb{Q})$ that switches α_1, α_2 and fixes α_3. Now we have $\alpha_1\xi_2^\iota + \alpha_2\xi_1^\iota + \alpha_3 = 0$. If $\xi_2^\iota \neq \xi_1$ then

$$\alpha_1/\alpha_2 = (\xi_1^\iota - \xi_2)/(\xi_1 - \xi_2^\iota) \in \mathbb{K}_0,$$

and we finish as before. Thus, $\xi_2^\iota = \xi_1$ (and $\xi_1^\iota = \xi_2$). Applying next the element that switches α_1, α_3 and fixes α_2, we obtain $\alpha_1 + \alpha_2\xi_1 + \alpha_3\xi_2 = 0$. Multiplying by $\xi_1 = \xi_2^{-1}$, we get $\alpha_1\xi_1 + \alpha_2\xi_1^2 + \alpha_3 = 0$. Hence $\alpha_2(\xi_1^2 - \xi_2) = 0$, which shows that $\xi_1^2 = \xi_2 = \xi_1^{-1}$. Thus, $\xi_1^3 = 1$, which implies that $\xi_1 = 1$ by our hypothesis. Hence $\xi_2 = \xi_1^\iota = 1$ as well, and we are done. □

Lemma 2.6. *Let λ be a root of $P(X) = X^3 - X^2 - X - 1$, and $n \in \mathbb{Z}$. Then $\alpha = \lambda^n/P'(\lambda)$ satisfies the hypothesis of Lemma 2.5.*

Proof. Clearly, $\alpha \in \mathbb{Q}(\lambda)$, which is a field of degree 3. If $\mathbb{Q}(\alpha) \neq \mathbb{Q}(\lambda)$ then $\alpha \in \mathbb{Q}$. Hence, denoting $\lambda_1, \lambda_2, \lambda_3$ the roots of $P(X)$, the three numbers $\lambda_i^n/P'(\lambda_i)$ must be equal. In particular, if λ_1 is the real root, and λ_2, λ_3 are the complex conjugate roots, then $\lambda_1^n/P'(\lambda_1) = \lambda_2^n/P'(\lambda_2)$, which implies that

$$n = \frac{\log|P'(\lambda_2)/P'(\lambda_1)|}{\log|\lambda_1/\lambda_2|} = -0.718\ldots \notin \mathbb{Z},$$

a contradiction.

Thus, $\mathbb{Q}(\alpha) = \mathbb{Q}(\lambda)$ is not a Galois extension of $\mathbb{Q}$. It remains to note that its Galois closure $\mathbb{Q}(\lambda_1, \lambda_2, \lambda_3)$ may not contain primitive cubic roots of unity, because the prime 3 is not ramified therein. □

Proof of Theorem 2.3. If $\sum_{i=1}^{3} \xi_i c_{\lambda_i} \lambda_i^n = 0$ then Lemmas 2.5 and 2.6 yield the conclusion $\xi_1 = \xi_2 = \xi_3$. Hence $T(n) = 0$, and we are done. □

Theorem 2.2 is proved in two steps. Using a Galois-theoretic argument similar to that of Lemma 2.5, but more involved, one reduces the problem to finding actual integral zeros of another linear recurrence, of order 4. Those are determined using standard technique, with logarithmic forms and the Baker-Davenport reduction. See [1] for the details.

3. p-Adic analytic functions

In this section we recall some very basic facts about p-adic analytic functions. Most of them are quite standard. All missing proofs, unless indicated otherwise, can be found in any standard text like [7].

Let p be a prime number and let $\mathbb{K}$ be a finite extension of $\mathbb{Q}_p$. We extend the standard p-adic absolute value $|\cdot|$ from $\mathbb{Q}_p$ to $\mathbb{K}$, so that $|p|_p = p^{-1}$. We will also use the additive valuation ν_p defined by $\nu_p(z) = -\log|z|_p/\log p$ for $z \in K^\times$, with the convention $\nu_p(0) = +\infty$.

For $a \in \mathbb{K}$ and $r > 0$ we denote $\mathcal{D}(a,r)$ and $\overline{\mathcal{D}}(a,r)$ the open and the closed disk with center a and radius r:

$$\mathcal{D}(a,r) = \{z \in K : |z-a|_p < r\}, \qquad \overline{\mathcal{D}}(a,r) = \{z \in K : |z-a|_p \le r\}.$$

We denote by $\mathcal{O}_{\mathbb{K}}$, or simply by $\mathcal{O}$ if this does not lead to a confusion, the ring of integers of $\mathbb{K}$:

$$\mathcal{O} = \{z \in \mathbb{K} : |z|_p \le 1\} = \overline{\mathcal{D}}(0,1).$$

We call $f : \mathcal{O} \to \mathcal{O}$ an analytic function if there is a sequence $\alpha_0, \alpha_1, \alpha_2, \ldots \in \mathcal{O}$ with $\lim_{n\to\infty} |\alpha_n|_p = 0$ such that

$$f(z) = \sum_{n=0}^{\infty} \alpha_n z^n \qquad (z \in \mathcal{O}).$$

Note that for any $b \in \mathcal{O}$ we have

$$f(z) = \sum_{k=0}^{\infty} \beta_k (z-b)^k, \tag{3.1}$$

where

$$\beta_k = \frac{f^{(k)}(b)}{k!} = \sum_{n=k}^{\infty} \binom{n}{k} \alpha_n b^{n-k}.$$

3.1. p-Adic order of values of an analytic function.

We start from the following trivial, but useful observation.

Proposition 3.1. *Let $f(z)$ be an analytic function. Then for any $a, b \in \mathcal{O}$ we have $|f(a) - f(b)|_p \le |a-b|_p$.*

Proof. Substituting $z = a$ into (3.1) and noting that $\beta_0 = f(b)$, we obtain

$$|f(a) - f(b)|_p = |b-a|_p \left| \sum_{k=1}^{\infty} \beta_k |a-b|^{k-1} \right|_p.$$

All terms in the sum on the right belong to $\mathcal{O}$, whence the result. □

Assume now that f is not identically 0. Then the set of zeros of f is finite, because it is a discrete subset of the compact set $\mathcal{O}$; we denote this set $\mathcal{A}$.

Theorem 3.2. *Let e be the ramification index of $\mathbb{K}/\mathbb{Q}_p$. Then there exists a positive integer k such that for every $i \in \{0, 1, \dots, p^k - 1\}$ we have one of the following two options.*

(C) *There exists $\kappa_i \in e^{-1}\mathbb{Z}$ such that for $z \in \mathcal{O}$ satisfying $z \equiv i \pmod{p^k}$ we have $\nu_p(f(z)) = \kappa_i$; in other words, $\nu_p(f(z))$ is constant on the residue class $z \equiv i \pmod{p^k}$.*

(L) *There exist*

$$a_i \in \mathcal{A}, \qquad \kappa_i \in e^{-1}\mathbb{Z}, \qquad \mu_i \in \mathbb{Z}_{>0}$$

such that for $z \in \mathcal{O}$ satisfying $z \equiv i \pmod{p^k}$ we have

$$\nu_p(f(z)) = \kappa_i + \mu_i \nu_p(z - a_i).$$

Proof. Let m be a positive integer, and for every $j \in \{0, 1, \dots, p^m - 1\}$ define $f_j(z) = f(j + p^m z)$. Clearly, if the statement holds true for every f_j then it holds for f as well. Taking m so large that every residue class $z \equiv j \pmod{p^m}$ contains at most one element from $\mathcal{A}$, we reduce the theorem to the case when f has at most one zero. If f does have a zero, say a, then, expanding

$$f(z) = \alpha_\mu (z - a)^\mu + \alpha_{\mu+1}(z - a)^{\mu+1} + \cdots,$$

with $\mu \geq 1$ and $\alpha_\mu \neq 0$, we note that the statement holds for f as soon as it holds for the analytic function $\alpha_\mu + \alpha_{\mu+1}(z - a) + \cdots$, which has no zero at all.

Thus, it suffices to consider the case $\mathcal{A} = \varnothing$. We need to show that the p-adic order $\nu_p(f(z))$ is constant on every residue class modulo a suitable power of p.

Since f does not vanish on $\mathcal{O}$, then, by compactness, $|f(z)|_p$ must be bounded from below by some strictly positive number. It follows that $f(z)$ belongs to one of the finitely many sets

$$\mathcal{O}^\times, \pi\mathcal{O}^\times, \dots, \pi^n\mathcal{O}^\times,$$

where π is a uniformizer of $\mathbb{K}$ and n is some positive integer. Note that $\nu_p(\pi) = e^{-1}$.

Since these sets are open, their inverse images by f are open as well. Hence each of these inverse images is a union of finitely many residue classes modulo some power of p. This completes the proof. □

3.2. **Vanishing of power series.** In this subsection we recall two fundamental results about vanishing of a power series on $\mathcal{O}$: Hensel's Lemma and Strassman's Theorem.

Hensel's Lemma is the principal technical tool of p-adic analysis. It is usually stated for polynomials, but in this article we need a slightly more general version, for power series.

Proposition 3.3 (Hensel's Lemma for power series)**.** *Let $b_0 \in \mathcal{O}$ be such that $|f(b_0)|_p < 1$ and $|f'(b_0)|_p = 1$. Then there exists a unique $b \in \mathcal{O}$ such that $f(b) = 0$ and $|b - b_0|_p < |f(b_0)|_p$.*

The proof can be found, for instance, in [3], see Theorems 8.2 and 9.4 therein, or in [11], see Theorem 27.6 therein.

The number of zeros can be estimated using Strassman's Theorem.

Theorem 3.4 (Strassman)**.** *Assume that $f(z)$ does not vanish identically on $\mathcal{O}$; equivalently, the coefficients α_0, α_1, ... are not all 0. Define μ as the largest m with the property*

$$|\alpha_m|_p = \max\{|\alpha_n|_p : n = 0, 1, \ldots\}.$$

(Since $|\alpha_n|_p \to 0$, such μ must exist.) Then $f(z)$ has at most μ zeros on $\mathcal{O}$.

The proof can be found in many sources; see, for instance, [2, Theorem 4.1].

3.3. **Functions** exp **and** log **in the p-adic domain.** We denote $\rho = p^{-1/(p-1)}$. Let us recall the definition and the basic properties of the p-adic exponential and logarithmic functions.

(1) For $z \in \mathcal{D}(0, \rho)$ we define

$$\exp(z) = \sum_{n=0}^{\infty} \frac{z^n}{n!}.$$

For $z, w \in \mathcal{D}(0, \rho)$ we have

$$|\exp(z) - 1|_p = |z|_p, \quad \exp(z + w) = \exp(z)\exp(w), \quad \exp'(z) = \exp(z).$$

(2) For $z \in \mathcal{D}(1, 1)$ we define

$$\log(z) = \sum_{n=1}^{\infty} \frac{(-1)^{n-1}(z-1)^n}{n}.$$

For $z, w \in \mathcal{D}(1, 1)$ we have

$$\log(zw) = \log(z) + \log(w), \quad \log'(z) = \frac{1}{z}.$$

(3) For $z \in \mathcal{D}(1, \rho)$ we have

$$|\log(z)|_p = |z - 1|_p, \quad \exp(\log(z)) = z.$$

(4) For $z \in \mathcal{D}(0, \rho)$ we have $\log(\exp(z)) = z$.

4. p-Adic analytic interpolation of the Tribonacci sequence

Recall that we denote $\Lambda = \{\lambda_1, \lambda_2, \lambda_3\}$ the set of roots of the polynomial

$$P(X) = X^3 - X^2 - X - 1.$$

Let p be a prime number and let $\mathbb{K} = \mathbb{Q}_p(\lambda_1, \lambda_2, \lambda_3)$ be the splitting field of $P(X)$ over $\mathbb{Q}_p$. As before, we denote $\mathcal{O}$ its ring of integers. The discriminant of $P(X)$ is -44. Hence, assuming in the sequel that $p \neq 2, 11$, the field $\mathbb{K}$ is unramified over $\mathbb{Q}_p$. In particular, with the notations from Section 3.3, we have

$$\mathcal{D}(0, \rho) = \mathcal{D}(0, 1), \qquad \mathcal{D}(1, \rho) = \mathcal{D}(1, 1), \qquad \overline{\mathcal{D}}(0, 1) = \mathcal{D}(0, p^{-1}).$$

We denote $d = [\mathbb{K} : \mathbb{Q}_p]$. There are three possibilities. If all the roots of $P(X)$ are in $\mathbb{Q}_p$ then $\mathbb{K} = \mathbb{Q}_p$ and $d = 1$. If $P(X)$ has exactly one root in $\mathbb{Q}_p$ then $d = 2$. Finally, if $P(X)$ is irreducible in $\mathbb{Q}_p$ then $d = 3$.

Recall that

$$T(n) = \sum_{\lambda \in \Lambda} c_\lambda \lambda^n, \qquad c_\lambda = \lambda P'(\lambda)^{-1}.$$

Note that, since $p \neq 2, 11$, we have $c_\lambda \in \mathcal{O}^\times$ for $\lambda \in \Lambda$. Recall also that $T(n) = 0$ if and only if $n \in \mathcal{Z}_T$. Note that $\Lambda \subset \mathcal{O}^\times$. Let $N = N_p$ be the order of the subgroup of the multiplicative group $(\mathcal{O}/p)^\times$ generated by Λ. In [9] this quantity is denoted

$\pi(p)$. Note that $N \mid p^d - 1$. When $d = 3$, we have the more precise divisibility relation $N \mid p^2 + p + 1$.

For $\ell \in \{0, 1, \dots, N-1\}$ we consider the analytic function $f_\ell : \mathbb{Z}_p \to \mathbb{Z}_p$ defined by

$$f_\ell(z) = \sum_{\lambda \in \Lambda} c_\lambda \lambda^\ell \exp\bigl(z \log(\lambda^N)\bigr). \tag{4.1}$$

Note that by the definition of N we have

$$\lambda^N \in \mathcal{D}(1,1) = \mathcal{D}(1,\rho),$$

so $f_\ell(z)$ is indeed well-defined for $z \in \mathbb{Z}_p$. Furthermore, for $m \in \mathbb{Z}$ we have

$$f_\ell(m) = T(\ell + mN) \in \mathbb{Z}. \tag{4.2}$$

Since $\mathbb{Z}$ is dense in $\mathbb{Z}_p$ and f_ℓ is continuous, we indeed have $f_\ell(z) \in \mathbb{Z}_p$ for $z \in \mathbb{Z}_p$.

Note also that $f_\ell(z)$ does not vanish identically on $\mathbb{Z}_p$: this also follows from equation (4.2).

5. Proof of Theorem 1.5

We use the terminology and the notation of Section 4. In this section p is a prime number, distinct from 2 and 11, and satisfying the following two conditions: $p \equiv 2 \pmod 3$ and $\Lambda \subset \mathbb{Q}_p$. The last condition means that $\mathbb{K} = \mathbb{Q}_p$ and $d = 1$. By the Chebotarev Density Theorem, the set of such p is infinite and, moreover, it is of density $1/12$ in the set of all primes.

We are going to show that for every such p both statements of Theorem 1.5 hold true. Actually, we will prove only the former statement:

$$n \equiv 1/3 \pmod{p-1} \Longrightarrow \nu_p(T(n)) \geq \nu_p(n - 1/3), \tag{5.1}$$

because the second statement, with $1/3$ replaced by $-5/3$, is proved absolutely similarly.

To start with, let us make the following observation: since $p \equiv 2 \pmod 3$, every element of $\mathbb{Z}_p^\times$ has a single cubic root in $\mathbb{Z}_p$. In particular, for every $\lambda \in \Lambda$ there is a well-defined cubic root $\lambda^{1/3} \in \mathbb{Z}_p$.

It turns out that these cubic roots are exactly those for which we have (2.2).

Proposition 5.1. *With our choice of the cubic roots $\lambda^{1/3}$ we have*

$$\sum_{\lambda \in \Lambda} c_\lambda \lambda^{1/3} = 0.$$

Proof. Assuming the contrary, we must have one of the options

$$c_{\lambda_1}\lambda_1^{1/3} + c_{\lambda_2}\lambda_2^{1/3} + \zeta c_{\lambda_3}\lambda_3^{1/3} = 0, \tag{5.2}$$

$$c_{\lambda_1}\lambda_1^{1/3} + \zeta c_{\lambda_2}\lambda_2^{1/3} + \zeta c_{\lambda_3}\lambda_3^{1/3} = 0, \tag{5.3}$$

$$c_{\lambda_1}\lambda_1^{1/3} + \zeta c_{\lambda_2}\lambda_2^{1/3} + \overline{\zeta} c_{\lambda_3}\lambda_3^{1/3} = 0, \tag{5.4}$$

where ζ and $\overline{\zeta}$ are the primitive cubic roots of unity. Option (5.3) reduces to (5.2), so we only need to rule out (5.2) and (5.4).

Note that $\zeta \notin \mathbb{Q}_p$ because $p \equiv 2 \bmod 3$. Therefore, by Galois conjugation, in the case (5.2) we also have $c_{\lambda_1}\lambda_1^{1/3} + c_{\lambda_2}\lambda_2^{1/3} + \overline{\zeta} c_{\lambda_3}\lambda_3^{1/3} = 0$. Hence, we get

$$(\zeta - \overline{\zeta}) c_{\lambda_3}\lambda_3^{1/3} = 0,$$

a contradiction.

Similarly, in the case (5.4) we also have $c_{\lambda_1}\lambda_1^{1/3} + \overline{\zeta}c_{\lambda_2}\lambda_2^{1/3} + \zeta c_{\lambda_3}\lambda_3^{1/3} = 0$. It follows that $(\zeta - \overline{\zeta})(c_{\lambda_2}\lambda_2^{1/3} - c_{\lambda_3}\lambda_3^{1/3}) = 0$, again a contradiction. □

Now we are in a position to prove (5.1). We define $N = N_p$ as in Section 4; note that in our special case $d = 1$ and so $N \mid p-1$. In particular, the residue class $1/3 \pmod N$ is well-defined.

Let $n \in \mathbb{Z}$ and $\ell \in \{0, \dots, N-1\}$ satisfy

$$n \equiv \ell \equiv 1/3 \pmod N.$$

We define $f_\ell(z)$ as in (4.1). Write $n = \ell + Nm$ and $1/3 = \ell + Nb$ with $m \in \mathbb{Z}$ and $b \in \mathbb{Z}_p \cap \mathbb{Q}$. We have clearly $T(n) = f_\ell(m)$. We claim that $f_\ell(b) = 0$. Indeed, for $\lambda \in \Lambda$ we have

$$\big(\lambda^\ell \exp(b\log(\lambda^N))\big)^3 = \lambda^{3(\ell+Nb)} = \lambda.$$

Since $\lambda^\ell \exp(b\log(\lambda^N) \in \mathbb{Z}_p$, it must be equal to the cubic root $\lambda^{1/3}$ specified above. Hence

$$f_\ell(b) = \sum_{\lambda\in\Lambda} c_\lambda \lambda^\ell \exp\big(b\log(\lambda^N)\big) = \sum_{\lambda\in\Lambda} c_\lambda \lambda^{1/3} = 0, \tag{5.5}$$

by Proposition 5.1.

Now we are done: Proposition 3.1 implies that

$$\nu_p(T(n)) = \nu_p(f_\ell(m) - f_\ell(b)) \geq \nu_p(m-b) = \nu_p(n - 1/3),$$

as wanted. Note that $p \equiv 2 \mod 3$ was only required to ensure that $3 \nmid N$. The argument above can be generalized for all p such that $3 \nmid N$ and $\Lambda \subset \mathbb{Q}_p$.

6. Analytic form of Conjectures 1.2 and 1.6

In this section p is a prime number distinct from $2, 3, 11$. We continue using the notation of Section 4.

We are going to show that Conjectures 1.2 and 1.6 have very natural interpretations in terms of the zeros of the functions $f_\ell(z)$.

Theorem 6.1.

(1) *The following three statements are equivalent.*
   (1) *Conjecture* 1.2 *holds for the given* p.
   (2) *For every* $\ell \in \{0, \dots, N-1\}$, *the zeros of the function* $f_\ell(z)$ *belong to* $N^{-1}\mathbb{Z}$.
   (3) *For every* ℓ *the following holds: if* $b \in \mathbb{Z}_p$ *is a zero of* $f_\ell(z)$ *then* $\ell + Nb \in \mathcal{Z}_T$.

(2) *The following three statements are equivalent.*
   (4) *Conjecture* 1.6 *holds for the given* p.
   (5) *For every* $\ell \in \{0, \dots, N-1\}$, *the zeros of the function* $f_\ell(z)$ *belong to* $\mathbb{Q} \cap \mathbb{Z}_p$.
   (6) *For every* ℓ *the following holds: if* $b \in \mathbb{Z}_p$ *is a zero of* $f_\ell(z)$ *then* $\ell + Nb \in \mathcal{Q}_T$.

Theorem 6.1 is very useful for producing counter-examples to Conjectures 1.2 and 1.6, see Section 8. More importantly, it provides a clear motivation why the conjectures can only be expected to hold for relatively few primes. Indeed, there is absolutely no reason to expect that every $f_\ell(z)$ would have only zeros in $\mathbb{Q}$, and it

is even less of a reason to expect that it would not vanish outside a fixed set of six elements.

Let us start with some lemmas.

Lemma 6.2. *If $b \in \mathbb{Q} \cap \mathbb{Z}_p$ is a zero of $f_\ell(z)$ then $\ell + Nb$ is a twisted rational zero of T, as defined in Section 2.*

Proof. Denote $a = \ell + Nb$ and for every $\lambda \in \Lambda$ choose some determination for λ^a.

Let m be a non-zero integer such that $mb \in \mathbb{Z}$. Then

$$\Big(\lambda^\ell \exp\big(b \log(\lambda^N)\big)\Big)^m = \lambda^{m\ell} \exp\big(mb \log(\lambda^N)\big) = \lambda^{ma}.$$

Hence $\lambda^\ell \exp\big(b \log(\lambda^N)\big) = \xi_\lambda \lambda^a$, where ξ_λ is a root of unity. It follows that

$$0 = f_\ell(b) = \sum_{\lambda \in \Lambda} \xi_\lambda c_\lambda \lambda^a,$$

as wanted. □

Lemma 6.3. *Assume that Conjecture* 1.6 *holds for a given p.*

(1) *Let $\ell \in \{0, 1, \dots, N-1\}$ and let $b \in \mathbb{Z}_p$ be a zero of $f_\ell(z)$. Then there exists $i \in \{0, 1, \dots, Q-1\}$ such that option* (L) *holds for the residue class of i, and such that $a_i = \ell + Nb$. In particular, $b \in \mathbb{Q}$, and if $a_i \in \mathbb{Z}$ then $b \in N^{-1}\mathbb{Z}$.*

(2) *Conversely, let $i \in \{0, 1, \dots, Q-1\}$ be such that option* (L) *holds for the residue class of i. Then there exists $\ell \in \{0, 1, \dots, N-1\}$ such that*

$$f_\ell\left(\frac{a_i - \ell}{N}\right) = 0.$$

Only item (1) will be used, but we include the converse statement for completeness.

Proof of item (1). This is the argument that already appeared in Section 1. Let (m_k) be a sequence of rational integers satisfying $m_k \equiv b \pmod{p^k}$, and set $n_k = \ell + Nm_k$. Then

$$\nu_p(T(n_k)) = \nu_p(f_\ell(m_k)) \geq \nu_p(n_k - b) \geq k,$$

and, in particular, $\nu_p(T(n_k) \to \infty$ as $k \to \infty$. Infinitely many of the numbers n_k belong to the same residue class $i \pmod{Q}$, and we will assume in the sequel that all n_k do, by taking a subsequence. Since $\nu_p(T(n_k)) \to \infty$, we must have option (L) for this residue class, and moreover, we must have $\nu_p(n_k - a_i) \to \infty$. Since we also have $\nu_p(n_k - (\ell + Nb)) \to \infty$, we obtain $a_i = \ell + Nb$. □

Proof of item (2). It is similar, but other way around. As in Remark 1.3, we find a sequence of integers (n_k) such that $n_k \equiv i \pmod{Q}$ and $n_k \equiv a_i \pmod{p^k}$. By choosing a subsequence, we find $\ell \in \{0, 1, \dots, N-1\}$ such that $n_k \equiv \ell \pmod{N}$ for all k.

Define $m_k = (n_k - \ell)/N$. The sequence (m_k) converges p-adically to $(a_i - \ell)/N$. Since $\nu_p(f_\ell(m_k)) = \nu_p(T(n_k) \geq k$, the sequence $(f_\ell(m_k))$ converges p-adically to 0. Hence $f_\ell((a_i - \ell)/N) = 0$. □

Proof of Theorem 6.1. The implications **(a)⇒(b)** and **(d)⇒(e)** follow from item (1) of Lemma 6.3. The converse implications **(b)⇒(a)** and **(e)⇒(d)** follow from Theorem 3.2, applied to the functions $f_\ell(z)$. Implications **(b)⇒(c)** and **(e)⇒(f)** follow by combining Lemma 6.2 with Theorems 2.3 and 2.2, respectively. Finally, the converse implications **(c)⇒(b)** and **(f)⇒(e)** are trivial. □

As a byproduct, we also established the following.

Corollary 6.4. *If Conjecture* 1.2 *holds for the given p, then the numbers a_i emerging in the residue classes with option* (L) *belong to the set $\mathcal{Z}_T$. If Conjecture* 1.6 *holds, then a_i belong to $\mathcal{Q}_T$.*

7. Detecting zeros of $f_\ell(z)$

To make use of Theorem 6.1, we must develop a practical method for locating zeros of $f_\ell(z)$. As in the previous sections, p is a prime number distinct from 2 and 11, and $\ell \in \{0, 1, \dots, N-1\}$.

7.1. **A non-vanishing condition.** To start with, let us give a simple sufficient condition for f_ℓ to be non-vanishing on $\mathbb{Z}_p$.

Proposition 7.1. *If $p \nmid T(\ell)$ then $f_\ell(z) \neq 0$ for $z \in \mathbb{Z}_p$.*

Proof. By the definition of N we have $f(n) \equiv f(\ell) \pmod{p}$ when $n \equiv \ell \pmod{N}$. In particular, for such n we have $|T(n)|_p = |T(\ell)|_p = 1$. In other words, for $m \in \mathbb{Z}$ we have $|f_\ell(m)|_p = 1$. By continuity, $|f_\ell(z)|_p = 1$ for $z \in \mathbb{Z}_p$. This completes the proof. □

7.2. **The first vanishing condition.** Now let us study sufficient conditions for $f_\ell(z)$ to have a zero $\mathbb{Z}_p$. As follows from above, the first condition must be

$$\boxed{p \mid T(\ell).} \tag{7.1}$$

This will be assumed for the rest of the section.

It will be more convenient to work with the function

$$g(z) = \frac{f_\ell(z)}{p}$$

instead of $f_\ell(z)$ itself. For further use, note that $g(z)$ has the expansion

$$g(z) = \sum_{k=0}^{\infty} \beta_k z^k \tag{7.2}$$

with the following properties:

$$\beta_k \in \mathbb{Z}_p \qquad (k = 0, 1, 2 \dots); \tag{7.3}$$

$$\beta_k \in p\mathbb{Z}_p \qquad (k = 2, 3, \dots); \tag{7.4}$$

$$|\beta_k|_p \to 0 \qquad (k \to \infty). \tag{7.5}$$

Indeed,

$$\beta_0 = g(0) = \frac{f_\ell(0)}{p} = \frac{T(\ell)}{p} \in \mathbb{Z} \tag{7.6}$$

by our choice of ℓ. Furthermore, we have

$$\beta_k = \frac{p^{k-1}}{k!} \sum_{\lambda \in \Lambda} c_\lambda \lambda^\ell \left(\frac{\log(\lambda^N)}{p} \right)^k. \tag{7.7}$$

Since $\lambda^N \equiv 1 \pmod{p}$, we have $\log(\lambda^N) \equiv 0 \pmod{p}$, which shows that the sum in (7.7) belongs to $\mathbb{Z}_p$. We also have $p^{k-1}/k! \in \mathbb{Z}_p$ when $p \geq 3$ and $k \geq 1$. Hence $\beta_k \in \mathbb{Z}_p$ for $k \geq 1$ as well. This proves (7.3).

Next, since the sum in (7.7) belongs to $\mathbb{Z}_p$, we have $\nu_p(\beta_k) \geq k - 1 - \nu_p(k!)$. It is known that $\nu_p(k!) < k/(p-1)$ for $k \geq 1$. In particular, $\nu_p(k!) < k/2$ for $p \geq 3$. It follows that $\nu_p(\beta_k) > 0$ for $k \geq 2$ and $\nu_p(\beta_k) \to +\infty$ as $k \to \infty$. This proves (7.4) and (7.5).

Note the following consequence of (7.4): for $z \in \mathbb{Z}_p$ we have

$$g'(z) \equiv g'(0) \pmod{p}. \tag{7.8}$$

Indeed,

$$g'(z) = \beta_1 + \sum_{k=2}^{\infty} k \beta_k z^{k-1}.$$

Here $\beta_1 = g'(0)$ and each term in the sum is divisible by p by (7.4).

7.3. **The second vanishing condition.** The second condition that we impose is

$$\boxed{g'(0) \neq 0 \pmod{p}.} \tag{7.9}$$

This condition means that $\beta_1 = g'(0) \in \mathbb{Z}_p^\times$. Hence there exists $b_0 \in \mathbb{Z}$ such that

$$b_0 \equiv -\beta_0 \beta_1^{-1} \pmod{p}. \tag{7.10}$$

Substituting $z = b_0$ into expansion (7.2), and using (7.4), we obtain

$$p \mid g(b_0). \tag{7.11}$$

On the other hand, (7.8) and (7.9) imply that $g'(b_0) \equiv g'(0) \not\equiv 0 \pmod{p}$. Together with (7.11) this can be expressed as

$$|g(b_0)|_p < 1, \qquad |g'(b_0)|_p = 1.$$

Now using Hensel's Lemma as given in Proposition 3.3, we find $b \in \mathbb{Z}_p$ such that $g(b) = 0$. Then we also have $f_\ell(b) = 0$.

Actually, we have even more.

Proposition 7.2. *Assume that* (7.1) *and* (7.9) *hold. Then $f_\ell(z)$ has exactly one zero on $\mathbb{Z}_p$.*

Proof. Existence of a zero is already proved above. To show uniqueness, we invoke Strassman's Theorem 3.4. Since $|\beta_1|_p = 1$ by (7.9), the quantity μ from Theorem 3.4 must be 1 by (7.4). Whence the result. □

8. Sufficient conditions for validity and for failure of Conjectures 1.2 and 1.6

To implement this in practice, we need to express condition (7.9) in terms of the Tribonacci numbers $T(n)$ rather than the function $g(z)$. This is not hard. For $z \in p\mathcal{O}$ we have

$$\log z \equiv z - 1 \pmod{p^2}.$$

In particular, for $\lambda \in \Lambda$ we

$$\frac{\log(\lambda^N)}{p} \equiv \frac{\lambda^N - 1}{p} \pmod{p}.$$

Hence,

(8.1)
$$g'(0) = \beta_1 = \sum_{\lambda\in\Lambda} c_\lambda \lambda^\ell \frac{\log(\lambda^N)}{p} \equiv \sum_{\lambda\in\Lambda} c_\lambda \lambda^\ell \frac{\lambda^N - 1}{p} \equiv \frac{T(\ell+N) - T(\ell)}{p} \pmod{p}.$$

Therefore condition (7.9) is equivalent to

(8.2)
$$\boxed{T(\ell+N) \not\equiv T(\ell) \pmod{p^2}.}$$

Now, to disprove Conjecture 1.2 for some prime number p, we must find ℓ such that both (7.1) and (8.2) are satisfied, and such that the resulting zero b of $f_\ell(z)$ satisfies

$$\ell + bN \notin \mathcal{Z}_T.$$

It suffices to show that

$$\ell + bN \not\equiv 0, -1, -4, -17 \pmod{p}.$$

Moreover, since $b \equiv b_0 \pmod{p}$, this can be re-written as

$$\ell + b_0 N \not\equiv 0, -1, -4, -17 \pmod{p}.$$

Using (7.10) and (8.1), this translates into

(8.3)
$$\boxed{u := \ell - \frac{T(\ell)}{p}\left(\frac{T(\ell+N) - T(\ell)}{p}\right)^{-1} N \not\equiv 0, -1, -4, -17 \pmod{p}.}$$

Similarly, when $p \neq 3$, then Conjecture 1.6 would fail if

(8.4)
$$\boxed{u \not\equiv 0, -1, -4, -17, 1/3, -5/3 \pmod{p}.}$$

Let us summarize what we proved.

Theorem 8.1. *Let $p \neq 2, 11$ be a prime number, and let $\ell \in \{0, 1, \dots N_p - 1\}$ be such that* (7.1), (8.2) *and* (8.3) *hold true. Then Conjecture* 1.2 *fails for this p. Similarly, if $p \neq 3$ and* (7.1), (8.2) *and* (8.4) *hold true then Conjecture* 1.6 *fails for this p.*

Now let us give sufficient conditions of validity of each conjecture.

Theorem 8.2. *Let p be a prime number distinct from* 2 *and* 11. *Assume that for every ℓ satisfying* (7.1), *condition* (8.2) *holds true as well, and the following also holds: $\ell \equiv a \pmod{N}$ for some $a \in \mathcal{Z}_T$. Then Conjecture* 1.2 *holds for this p.*

Theorem 8.3. *Let p be a prime number satisfying $\Lambda \subset \mathbb{Q}_p$ and $3 \nmid N$. Assume that for every ℓ satisfying* (7.1)*, condition* (8.2) *holds true as well, and the following also holds: $\ell \equiv a \pmod N$ for some $a \in \mathcal{Q}_T$. Then Conjecture* 1.6 *holds for this p.*

Proof of Theorem 8.2. Fix $\ell \in \{0, 1, \dots, N-1\}$. If $p \nmid T(\ell)$ then $f_\ell(z)$ has no zeros on $\mathbb{Z}_p$, see Proposition 7.1. Now assume that $p \mid T(\ell)$. Proposition 7.2 implies that $f_\ell(z)$ has a single zero on $\mathbb{Z}_p$.

Now let $a \in \mathcal{Z}_T$ be such that $\ell \equiv a \pmod N$. Write $a = \ell + Nb$ with $b \in \mathbb{Z}$. Then $f_\ell(b) = T(\ell + Nb) = 0$. Thus, the single zero of $f_\ell(z)$ is b.

We have just showed that condition **(c)** of Theorem 6.1 holds true for this p. The theorem is proved. □

The proof of Theorem 8.3 is the same, with the exception that this time we may have $b \notin \mathbb{Z}$. However, when $\Lambda \subset \mathbb{Q}_p$, $p \neq 2, 11$ and due to $3 \nmid N$, we still have $f_\ell(b) = 0$, see (5.5).

9. The proofs of Theorems 1.4, 1.7, and 1.8

We start with the negative part (part (i)) of Theorem 1.7. We implemented the algorithms implied by Theorem 8.1 in Mathematica for all primes $p \leq 600$. There are 109 primes $p \leq 600$. For each prime p, we first computed $N := N_p$, the period of $(T_n)_{n \in \mathbb{Z}}$ modulo p. Then for each p we searched ℓ such that (7.1), (8.2) and (8.3) all hold true. This calculation took a few minutes and found such an example ℓ for all $p \leq 600$ except for $p \in \{2, 3, 11, 83, 103, 163, 397\}$. See Table 1 for the actual data. This proves the negative part of Theorem 1.7.

As for part (ii) of Theorem 1.7, when $p \in \{83, 397\}$, we have that $N = N_p$ is 287 and 132, respectively. In both cases, the only $\ell \in \{0, 1, \dots, N-1\}$ such that $T(\ell) \equiv 0 \pmod p$ are $\ell \equiv -17, -4, -1, 0 \pmod N$. Furthermore for $\ell \in \mathcal{Z}_T$, we have $(T(N+\ell) - T(\ell))/p = T(N+\ell)/p \not\equiv 0 \pmod p$. Thus, taking $\ell \in \mathcal{Z}_T$ and writing for positive integers $n \equiv \ell \pmod N$, $z = (n-\ell)/N$, we have that

$$T(n) = f_\ell(z) = pg(z) = p \sum_{k \geq 0} \beta_k z^k.$$

Note that $\beta_0 = g(0) = T(\ell)/p = 0$, and $\beta_1 = g'(0) \equiv T(N+\ell)/p \pmod p$, so $|\beta_1|_p = |g'(0)|_p = 1$. Further, since $\nu_p(p^{k-1}/(k-1)!) \geq 1$ for all $k \geq 2$, it follows that $|\beta_k|_p < 1$ for $k \geq 2$. This shows that

$$\nu_p(T(n)) = 1 + \nu_p(g(z)) = 1 + \nu_p\left(\sum_{k \geq 1} \beta_k z^k\right) = 1 + \nu_p(z) = 1 + \nu_p(n - \ell),$$

which proves part (ii) of Theorem 1.7.

Theorem 1.8 is proved similarly, only (8.3) is exchanged for (8.4) and $\mathcal{Z}_T$ for $\mathcal{Q}_T$.

Proof of Theorem 1.4. For $p = 3$, we have $N = 13$. The only $\ell \in \{0, \dots, 12\}$ such that $T(\ell) \equiv 0 \pmod 3$ are $\ell \in \{0, 7, 9, 12\}$. When $\ell = 7$, the subsequence $T(13n+\ell)$ is always 6 modulo 9, and so $v_3(T(n)) = 1$ if $n \equiv 7 \pmod{13}$.

TABLE 1. Data for the proofs of Theorems 1.7 and 1.8. A * means that for this prime, Theorem 1.8 does not conclude.

p	N	ℓ	u	p	N	ℓ	u	p	N	ℓ	u
5	31	21	2	179	32221	100	114	379	48007	309	76
7	48	5	1	181	10981	25	66	383	147073	219	338
13	168	6	4	191	36673	72	22	389	151711	1739	354
17	96	28	7	193	4656	171	76	401*	400	265	132
19	360	18	12	197	3234	382	84	409	41820	365	310
23	553	29	15	199	198	26	40	419*	418	277	138
29	140	77	24	211	5565	83	203	421	420	118	214
31	331	14	22	223	16651	361	38	431	61920	465	51
37	469	19	17	227	17176	34	57	433	62641	385	334
41	560	35	15	229	17557	249	61	439	6424	781	160
43	308	82	11	233	9048	36	126	443	196693	516	21
47*	46	31	16	239	4760	28	85	449	202051	107	229
53*	52	33	16	241	29040	506	57	457	34808	858	30
59	3541	64	34	251	63253	304	218	461	35420	192	9
61	1860	68	34	257	256	54	34	463	71611	624	199
67	1519	100	43	263	23056	37	214	467	218557	1269	70
71	5113	132	62	269*	268	177	88	479	76480	56	8
73	5328	31	30	271	73440	331	165	487	79219	131	85
79	3120	18	76	277	12788	61	191	491	10045	802	289
89	8011	109	8	281	13160	536	62	499*	166	109	331
97	3169	19	51	283	13348	777	193	503	42168	107	497
101	680	186	23	293	28616	458	200	509	259591	1228	433
107	1272	184	52	307	31416	30	163	521	271963	2058	220
109	990	105	62	311	310	123	58	523	273528	237	16
113	12883	172	15	313	32761	29	184	541	58536	633	200
127	5376	586	30	317	100807	36	186	547	149604	104	72
131	5720	79	101	331	36631	188	4	557	103416	509	424
137	18907	11	5	337	16224	320	103	563	52828	87	232
139	3864	34	49	347	40136	156	244	569	53960	322	49
149	7400	10	38	349	17400	1428	33	571	40755	527	155
151	2850	223	142	353	124963	95	38	577	111169	361	85
157	8269	71	107	359	42960	1204	115	587*	293	96	194
167	9296	41	68	367	45019	692	99	593	3256	849	422
173	2494	314	25	373	139128	279	188	599	598	257	485

Next assume that $\ell = 0,\ -1$. Then $g(0)$ is congruent modulo 3 to one of $T(13)/3,\ T(12)/3$ and they are both 0, so we need additional terms. We have

$$\begin{aligned}\beta_1 &= \sum_{\lambda\in\Lambda} c_\lambda \lambda^\ell \left(\frac{\log \lambda^N}{3}\right)\\ &\equiv \sum_{\lambda\in\Lambda} c_\lambda \lambda^\ell \left(\frac{\lambda^N-1}{3} - \frac{(\lambda^N-1)^2}{2\cdot 3}\right) && \pmod{3^2}\\ &\equiv \frac{T(N+\ell)-T(\ell)}{3} - \frac{T(2N+\ell)-2T(N+\ell)+T(\ell)}{2\cdot 3} && \pmod{3^2}.\end{aligned}$$

For both $\ell = 0,\ -1$, we have $\nu_3((T(N+\ell)-T(\ell))) = 2$ and

$$\nu_3(T(2N+\ell)-2T(N+\ell)+T(\ell)) = 3.$$

Thus, $\nu_3(\beta_1) = 1$. For $j \geq 4$, we get that $\nu_3(\beta_j) \geq \nu_3(3^{j-1}/j!) \geq 2$. It remains to study $\nu_3(\beta_j)$ for $j = 2, 3$. But we have

$$\begin{aligned}\beta_j &= \frac{3^{j-1}}{j!} \sum_{\lambda \in \Lambda} c_\lambda \lambda^\ell \left(\frac{\log \lambda^N}{3} \right)^j \\ &\equiv \frac{3^{j-1}}{j!} \sum_{\lambda \in \Lambda} c_\lambda \lambda^\ell \left(\frac{\lambda^N - 1}{3} \right)^j && \pmod{3^j} \\ &\equiv \frac{3^{j-1}}{j!} \left(\frac{\sum_{i=0}^{j} (-1)^{j-i} \binom{j}{i} T((j-i)N + \ell)}{3^j} \right) && \pmod{3^j},\end{aligned}$$

and computations show that for $j = 2, 3$, we have

$$\begin{aligned}\nu_3(T(2N + \ell) - 2T(N + \ell) + T(\ell)) &= 3; \\ \nu_3(T(3N + \ell) - 3T(2N + \ell) + 3T(N + \ell) - T(\ell)) &= 5.\end{aligned}$$

Since also $\nu_3(3^{j-1}/j!) = 1$ for $j = 2, 3$, we get that $\nu_3(\beta_2) \geq 2$, $\nu_3(\beta_3) \geq 2$. Thus, for $n \equiv \ell \pmod{13}$, we have

$$\nu_3(T(n)) = \nu_3 \left(\beta_1 z + \sum_{k \geq 2} \beta_k z^k \right) = \nu_3(\beta_1 z) = 2 + \nu_3(n - \ell).$$

It remains to study the case $\ell = 9$. For this, we take $N_1 = 3N = 39$. This case then becomes $\ell \equiv -4, -17, 9 \pmod{39}$. For $\ell = 9$, the subsequence $T(3Nn + \ell)$ is constantly $3^4 \mod 3^5$, and so $v_3(T(n)) = 4$ for all $n \equiv 9 \mod 3N$. So let $\ell = -4, -17$. Then, if $n \equiv \ell \pmod{3N}$, putting $z = (n - \ell)/3N$, we get

$$T(n) = 3^2 g(z),$$

where now

$$g(z) = \sum_{\lambda \in \Lambda} c_\lambda \lambda^\ell \left(\frac{\exp(\log \lambda^{3Nz})}{3^2} \right) = \sum_{k \geq 0} \beta_k z^k.$$

For both possibilities of ℓ, $\beta_0 = 0$. However, modulo 3^4 we have

$$\begin{aligned}\beta_1 &= \sum_{\lambda \in \Lambda} c_\lambda \lambda^\ell \left(\frac{\log \lambda^{3N}}{3^2} \right) \\ &\equiv \frac{1}{3^2} \sum_{\lambda \in \Lambda} c_\lambda \lambda^\ell \left(\lambda^{3N} - 1 - \frac{(\lambda^{3N} - 1)^2}{2} \right) \\ &\equiv \frac{1}{3^2} \left(T(3N + \ell) - T(\ell) - \frac{T(2 \cdot 3N + \ell) - 2T(3N + \ell) + T(\ell)}{2} \right).\end{aligned}$$

In both cases, $\nu_3(T(3N+\ell) - T(\ell) = 5$ but $\nu_3(T(2 \cdot N + \ell) - 2T(3N + \ell) + T(\ell)) = 6$. Thus, $\nu_3(\beta_1) = 3$. Since $v_3(\beta_j) \geq \nu_3(3^{2(j-1)}/j!) \geq 4$ for $j \geq 4$, we only need to calculate β_2 and β_3. We find that

$$\beta_2 \equiv \frac{3^2}{2!} \left(\frac{T(2 \cdot 3N + \ell) - 2T(3N + \ell) + T(\ell)}{3^4} \right) \equiv 0 \pmod{3^4}$$

and

$$\beta_3 \equiv \frac{3^4}{3!} \left(\frac{T(3 \cdot 3N + \ell) - 3T(2 \cdot 3N + \ell) + 3T(3N + \ell) - T(\ell)}{3^6} \right) \equiv 0 \pmod{3^6}.$$

We conclude that

$$\begin{aligned}\nu_3(T(n)) &= \nu_3\left(3^2\left(\sum_{k\geq 0}\beta_k z^k\right)\right)\\ &= \nu_3(3^2\beta_0 z^k)\\ &= 5+\nu_3((n+\ell)/39)\\ &= 4+\nu_3(n+\ell),\end{aligned}$$

which completes the proof of this theorem. □

For the primes $p \in \{11, 103, 163\}$ not covered by Theorem 1.7, as we previously said, our methods do not handle 11. As for $p \in \{103, 163\}$, a computer calculation found that for such primes whenever $\ell \in \{0, 1, \ldots, N-1\}$ is such that condition (7.1) is satisfied, then (8.2) holds but (8.3) fails, so our method could not conclude. For $p = 163$, $N_p = 162 = 2 \cdot 3^4$, and the orders of λ_1, λ_2 and λ_3 in $\mathbb{Z}_p/p\mathbb{Z}_p$ are all divisible by 3. Thus, for $\ell \in \mathcal{Z}_T$ and $n \in \mathbb{Z}$ satisfying $n \equiv \ell \mod N_p$, $n + \frac{N_p}{3} \equiv \ell \mod N_p$ or $n + \frac{2N_p}{3} \equiv \ell \mod N_p$, $p \mid T_n$. This pattern causes (8.3) to fail, and a more careful analysis is required. For $p = 103$, a similar phenomenon occurs.

Similarly, for the primes $p \in \{11, 47, 53, 103, 163\}$ which are not covered by Theorem 1.8, our methods fail. Again, 11 is excluded and for $p \in \{103, 163\}$ we cannot conclude for the same reason. Moreover, $p \in \{47, 53\}$ suffer the problem that modulo N, -17 is congruent to either $1/3$ or $-5/3$, and so congruences modulo p are too weak to conclude.

Using Sagemath, we analyzed all 1229 primes up to 10^4. Conjecture 1.2 holds for 18 primes and Conjecture 1.6 for 52 primes. For 58 primes our methods neither prove nor disprove whether Conjecture 1.2 holds. All, save for $p = 11$, exhibit the same behavior as $p = 163$. For 4 primes, our methods neither prove nor disprove Conjecture 1.6. The only new prime in this set is 2621, for which (8.2) fails once.

Save for 11, our methods deal with all primes $p < 10^4$ such that $\Lambda \not\subset \mathbb{Q}_p$. Only for $p = 83$, our algorithm does not reject Conjectures 1.2 and 1.6 directly. Such primes are rare (but not non-existent. For example, for 23977 we cannot decide whether Conjecture 1.2 holds while 25121 satisfies Conjecture 1.2). As N_p is generally much larger for these primes, we ran our algorithm for all 13059 primes $p < 10^6$ such that $\Lambda \subset \mathbb{Q}_p$. Of those, 1186 (9.1%) and 3269 (25.0%) primes satisfy Conjectures 1.2 and 1.6, respectively. For 3451 (26.4%) and 3 (< 0.1%) primes, respectively, Conjectures 1.2 and 1.6 cannot be decided using our methods. For the remaining 5150 primes (39.4%), both conjectures fail.

10. Conjectures and heuristics

Let $\mathcal{ML}$ and $\mathcal{NMLR}$ be the subsets of primes p such that Conjecture 1.2 holds and Conjecture 1.6 fails, respectively. We propose Conjecture 10.1.

Conjecture 10.1. *Both subsets $\mathcal{ML}$ and $\mathcal{NMLR}$ are infinite. In fact, they are both of positive lower density as subsets of the set of all primes.*

We conclude by offering some heuristics to support our conjecture. Let k be a large positive integer. The splitting field of the polynomial

$$g(X) = f(X^k) = X^{3k} - X^{2k} - X^k - 1$$

is $\mathbb{L}_k = \mathbb{Q}(\sqrt[k]{\alpha}, \sqrt[k]{\beta}, \zeta_k)$, where ζ_k is some primitive root of unity of order k. The degree of $\mathbb{L}_k$ is at most $k^2\phi(k)$, where $\phi(k)$ is the Euler function of k. By the Chebotarev Density Theorem, the primes such that $p \equiv 1 \pmod{k}$ and also $\alpha^{(p-1)/k} \equiv \beta^{(p-1)/k} \equiv 1 \pmod{p}$ form a set of density which is at least $1/(k^2\phi(k))$. For such primes, $N \mid (p-1)/k$, so N is small. Since $N \leq (p-1)/k$ a proportion of only about $1/k$ residues modulo p (at most) are in the image of $\{T_\ell \pmod{p} : 0 \leq \ell \leq N-1\}$ which suggests that the probability of having an additional zero modulo p; i.e., a positive integer ℓ such that $T_\ell \equiv 0 \pmod{p}$ and $\ell \not\equiv 17, -4, -1, 0 \pmod{p}$ should be at most $1/k$. Thus, a positive proportion of such primes, maybe at least $(k-1)/(k^3\phi(k))$ of them, have the property that $T_\ell \equiv 0 \pmod{p}$ implies $\ell \equiv -17, -4, -1, 0 \pmod{p}$. For such primes, $f_\ell(0) = 0$, so

$$f_\ell(z) = p\sum_{k=1}^{\infty} \beta_k z^k.$$

If additionally (8.2) is satisfied, so $\beta_1 \not\equiv 0 \pmod{p}$, which we conjecture happens for most such primes, then we would get that $\nu_p(T_n) = 0$ provided that we have $n \not\equiv -17, -4, -1, 0 \pmod{p}$ and $\nu_p(T_n) = 1 + \nu_p(n-c)$ for $n \equiv c \pmod{p}$, with $c \in \{-17, -4, -1, 0\}$. This heuristic suggests that $\mathcal{ML}$ is infinite and of positive lower density.

For $\mathcal{NMLR}$ let p be a prime such that $p \equiv 2 \pmod{3}$ and $f(X) \pmod{p}$ is irreducible. By the Chebotarev Density Theorem the set of such primes has density $1/6$. For them $N \mid p^2+p+1$. Let $P(m)$ be the largest prime factor of the positive integer m. For each fixed $u \in (0,1)$, the positive integers n such that $P(n) \leq n^u$ are called *smooth*. It is known that the set of smooth numbers has a density $\rho(u)$, where ρ is the Dickman function. It is conjectured that numbers of the form $g(p)$ where $g(X)$ is some irreducible polynomial should behave like random integers with respect to smoothness and in particular that $P(g(p)) > g(p)^u$ should hold for a positive proportion of primes p, but this has only been proved for linear polynomials $g(X)$ and values of u not very close to 1 (for example, Fouvry [6] proved that for any non-zero integer a the inequality $P(p-a) > p^{0.67}$ holds for a positive proportion of primes p). So, let us assume that there is a positive proportion of primes p such that $f(X)$ is irreducible modulo p and $P(p^2+p+1) > p^{1.6}$. Let p be such a prime and let $q = P(p^2+p+1)$. Then $N \mid p^2+p+1$. If $q \nmid N$, then $N \mid (p^2+p+1)/q < p^{0.4}$. However, an argument of Erdős and Murty from [4] shows that for any positive real number X the number of primes $p \leq X$ which divide $N_{\mathbb{K}/\mathbb{Q}}(\alpha^k)$ for some $k \leq X^{0.4}$ is $O(X^{0.8})$ which is $o(\pi(X))$ as $X \to \infty$. This shows that for most of our primes p (namely, $p \equiv 2 \pmod{3}$, $f(X) \pmod{p}$ is irreducible and $P(p^2+p+1) > p^{1.6}$), we have that $q \mid N$. In particular, $N > p^{1.6}$. Now Theorem 7.2 in [5] tells us that

$$\#\{0 \leq \ell \leq N-1 : T_\ell \equiv 0 \pmod{p}\} = \frac{N}{p} + O(p^{1/2}) = (1+o(1))\frac{N}{p}.$$

Thus, there are many ℓ in $[0, N-1]$ with $T_\ell \equiv 0 \pmod{p}$. Of these not all might create p-adic zeros since for example, it might happen that $(T_{N+\ell} - T_\ell)/p \equiv 0 \pmod{p}$, or even if this number is non-zero modulo p, it might be that (8.4) is not satisfied. However, since we have no reason to believe that the above numbers are anything but random modulo p, we assume that the first condition fails with probability $1/p$ and the second one fails with probability $6/p$, getting in this way that the number of $\ell \in [0, N-1]$ such that $\ell \not\equiv -17, -4, -1, 0 \pmod{p}$ and both conditions (8.2) and (8.4) hold is $(1+o(1))N/p + O(N/p^2) = (1+o(1))N/p$. So,

for most of such primes Conjecture 1.6 would fail, which suggests that $\mathcal{N}MLR$ is of positive lower density.

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