ASYMPTOTIC VALUATIONS OF SEQUENCES SATISFYING FIRST ORDER RECURRENCES

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Abstract. Let t_n be a sequence that satisfies a first order homogeneous recurrence $t_n = Q(n)t_{n-1}$, where Q is a polynomial with integer coefficients. We describe the asymptotic behavior of the p-adic valuation of t_n.

1. Introduction

The p-adic valuation $\nu_p(x)$, for $x \in \mathbb{Q}$, $x \neq 0$, is defined by

$$x = p^{\nu_p(x)} \frac{a}{b}, \tag{1.1}$$

where $a, b \in \mathbb{Z}$ and p divides neither a nor b. The value $\nu_p(0)$ is defined to be ∞.

In this paper we establish the asymptotic behavior of the p-adic valuation of sequences that satisfy first order recurrences

$$t_n = Q(n)t_{n-1}, \; n \geq n_0, \tag{1.2}$$

where Q is a polynomial with integer coefficients and $n_0 \in \mathbb{N}$. Let v be the maximum modulus of all the (possibly none) zeros of Q in $\mathbb{Z}$. If $v > 0$, we choose $n_0 > v$, to guarantee $t_n \neq 0$. Without loss of generality, we always assume that $n_0 = 0$ and $t_0 = 1$. The notation $t_n(Q)$ is used while refering to (1.2).

The identity

$$\nu_p(t_n(Q)) = \sum_{i=1}^{n} \nu_p(Q(i)), \tag{1.3}$$

shows that only the zeros of Q in $\mathbb{Z}/p\mathbb{Z}$ contribute to the value of $\nu_p(t_n(Q))$. Moreover, it shows that it suffices to consider the case where $Q(x)$ is irreducible over $\mathbb{Z}$. This assumption will be enforced. The asymptotic analysis employs Hensel's lemma. The version stated here is reproduced from [3].

Lemma 1.1. *(Hensel's Lemma) Let f be a polynomial with coefficients in the p-adic integers $\mathbb{Z}_p$. Write $f'(x)$ for its formal derivative. If $f(x) \equiv 0 \bmod p$ has a solution a_1, satisfying $f'(a_1) \not\equiv 0 \bmod p$, then there is a unique p-adic integer a such that $f(a) = 0$ and $a \equiv a_1 \bmod p$.*

We now state our main result. It provides an asymptotic description of the valuation of the sequence t_n, defined by (1.2).

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Theorem 1.2. *Let* $Q(x) \in \mathbb{Z}[x]$. *Assume* $Q(x)$ *factors over* $\mathbb{Z}_p$ *as*

$$Q(x) = \left(\prod_{j=1}^{m} (x - \beta_j) \right) Q_1(x), \tag{1.4}$$

where $Q_1(x) \not\equiv 0 \bmod p$ *for any* $x \in \mathbb{Z}_p$. *Then the sequence* $\{t_n\}$, *defined by (1.2), satisfies*

$$\nu_p(t_n(Q)) = \frac{mn}{p-1} + O(\log n). \tag{1.5}$$

Section 2 contains the proof of Theorem 1.2 and Section 3 presents examples illustrating the main result.

2. The Proof

Assume Q has no roots in $\mathbb{N} \cup \{0\}$. The general case is reduced to this one by a shift of the independent variable. Using (1.4) it suffices to the study of the asymptotic behavior of

$$\nu_p \left(\prod_{i=1}^{n} (i - \beta_j) \right). \tag{2.1}$$

Define

$$r_{jn} = \max\{k : p^k | (i - \beta_j) \text{ for some } 1 \leq i \leq n\}. \tag{2.2}$$

The value of (2.1) is given by

$$\sum_{k=1}^{r_{jn}} \#\{1 \leq i \leq n : p^k | (i - \beta_j)\}. \tag{2.3}$$

Let $\gamma_{jk} \in \mathbb{Z}$ be such that

$$\beta_j \equiv \gamma_{jk} \bmod p^k. \tag{2.4}$$

Then $p^k | (i - \beta_j)$ if and only if $i \equiv \gamma_{jk} \bmod p^k$. Since the number of such i between 1 and n is either

$$\left\lfloor \frac{n}{p^k} \right\rfloor \text{ or } \left\lfloor \frac{n}{p^k} \right\rfloor + 1, \tag{2.5}$$

we have

$$\sum_{k=1}^{r_{jn}} \left\lfloor \frac{n}{p^k} \right\rfloor \leq \nu_p \left(\prod_{i=1}^{n} (i - \beta_j) \right) \leq \sum_{k=1}^{r_{jn}} \left\lfloor \frac{n}{p^k} \right\rfloor + 1. \tag{2.6}$$

By definition $p^{r_{jn}}$ divides $|Q(i)|$ for some $1 \leq i \leq n$. Therefore

$$p^{r_{jn}} \leq |Q(i)| \leq \max\{|Q(1)|, |Q(2)|, \cdots, |Q(n)|\} \leq Cn^{\deg(Q)}, \tag{2.7}$$

where the constant C depends only on the coefficients of Q. This implies that $r_{jn} = O(\log n)$. From (2.6) we now obtain

$$\sum_{k=1}^{r_{jn}} \left(\frac{n}{p^k} - 1 \right) \leq \nu_p \left(\prod_{i=1}^{n} (i - \beta_j) \right) \leq \sum_{k=1}^{r_{jn}} \left(\frac{n}{p^k} + 1 \right) \tag{2.8}$$

and

$$\nu_p\left(\prod_{i=1}^{n}(i-\beta_j)\right) = \frac{n}{p-1} - \frac{np^{-r_{jn}}}{p-1} + O(\log n). \tag{2.9}$$

The bound $r_{jn} \geq \lfloor \log n)/\log p\rfloor$ shows that the second term in (2.9) satisfies

$$\frac{np^{-r_{jn}}}{p-1} = O(1), \tag{2.10}$$

and we conclude that

$$\nu_p\left(\prod_{i=1}^{n}(i-\beta_j)\right) = \frac{n}{p-1} + O(\log n). \tag{2.11}$$

Theorem 1.2 has been established.

We now consider the factorization (1.4). If all zeros of $Q(x)$ in $\mathbb{Z}/p\mathbb{Z}$ satisfy the hypothesis of Hensel's Lemma, then $Q(x)$ factors over the p-adic numbers as

$$Q(x) = \left(\prod_{j=1}^{z_p(Q)}(x-\beta_j)\right) Q_1(x), \tag{2.12}$$

where β_j are p-adic integers and $Q_1(x) \equiv 0 \bmod p$ has no solutions in $\mathbb{Z}/p\mathbb{Z}$. Therefore we have

Corollary 2.1. *Let $Q(x) \in \mathbb{Z}[x]$. Assume each of the roots of Q satisfy the hypothesis of Hensel's Lemma. Let $z_p(Q)$ denote the number of roots of Q in $\mathbb{Z}/p\mathbb{Z}$, that is,*

$$z_p(Q) = \left|\{b \in \{1,2,\cdots,p\} : Q(b) \equiv 0 \bmod p\}\right|. \tag{2.13}$$

Then the sequence $\{t_n\}$, defined by (1.2), satisfies

$$\nu_p(t_n(Q)) = \frac{z_p(Q)n}{p-1} + O(\log n). \tag{2.14}$$

3. Examples

In this section we present some examples illustrating Theorem 1.2.

Definition 3.1. Given a polynomial $Q(x) \in \mathbb{Z}[x]$ and a prime p, we say that $a \in \mathbb{Z}/p\mathbb{Z}$ is a *Hensel zero* of Q if $Q(a) \equiv 0 \bmod p$ and $Q'(a) \not\equiv 0 \bmod p$. The prime p is called a *Hensel prime* for Q if all the zeros of Q in $\mathbb{Z}/p\mathbb{Z}$ are Hensel zeros.

If $Q(x)$ is irreducible over $\mathbb{Z}$, any prime that does not divide the discriminant $D(Q)$ of Q is a Hensel prime. This follows from the fact that $D(Q)$ is the resultant of Q and Q' (see [2]), and so there exist polynomials $A(x)$ and $B(x)$ with integers coefficients such that $A(x)Q(x) + B(x)Q'(x) = D(Q)$.

Corollary 2.1 is now expressed as:

Corollary 3.1. *Let p be a Hensel prime for $Q(x) \in \mathbb{Z}[x]$. Then the sequence $\{t_n\}$ satisfies*

$$\nu_p(t_n(Q)) = \frac{z_p(Q)n}{p-1} + O(\log n). \tag{3.1}$$

This is illustrated in the next example.

Example 3.2. Let $Q(x) = x^2 - 17$. The discriminant of Q is given by $D(Q) = 68 = 2^2 \cdot 17$. Therefore the non-Hensel primes for Q are $p = 2$ and 17. For all other primes p we have

$$\nu_p(t_n(Q)) \sim \frac{z_p(Q)n}{p-1} = \frac{2n}{p-1}, \tag{3.2}$$

if 17 is a square modulo p and $\nu_p(t_n) = 0$, otherwise.

The cases $p = 2$ and $p = 17$ are discussed next. For $p = 2$, note that only $1 \in \mathbb{Z}/2\mathbb{Z}$ is a zero modulo 2 with $Q(1) = -16$ and $Q'(1) = 2$. The analysis of the asymptotics of $\nu_2(t_n)$ requires a modified version of Hensel's Lemma in which the condition $f'(a_1) \not\equiv 0 \bmod p$ is replaced by $|f(a_1)|_p < (|f'(a_1)|_p)^2$. See [1] for details. The inequality $|Q(1)|_2 < (|Q'(1)|_2)^2$ shows that the root $a = 1 \in \mathbb{Z}/2\mathbb{Z}$ can be lifted to an element $\alpha \in \mathbb{Z}_2$ with $Q(\alpha) = 0$. Then $-\alpha$ is the second root of $Q(x)$ and we conclude that $\nu_2(t_n) \sim 2n$. Figure 1 shows $\nu_2(t_n)$. For the prime $p = 17$, this method does not apply because $Q(x)$ is irreducible over $\mathbb{Z}_{17}$. The result $\nu_{17}(t_n) \sim n/17$ will be established as a consequence of Theorem 3.4.

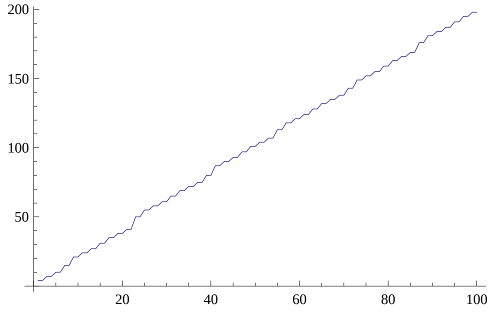

FIGURE 1. The valuation $\nu_2(t_n)$ for $Q(x) = x^2 - 17$.

Example 3.3. Let $\Phi_p(x) = x^{p-1} + x^{p-2} + \cdots + 1$ for p an odd prime. This polynomial is irreducible over $\mathbb{Z}_p$ so the general method described above does not apply. However, it is easy to establish

$$\nu_p(\Phi_p(x)) = \begin{cases} 0 & \text{if } x \not\equiv 1 \bmod p \\ 1 & \text{if } x \equiv 1 \bmod p. \end{cases} \tag{3.3}$$

We conclude that $\nu_p(t_n(\Phi_p)) \sim n/p$. Figure 2 shows $\nu_5(t_n(\Phi_5))$.

The next theorem provides a framework for irreducible polynomials that includes the previous two examples.

Theorem 3.4. *Assume that $Q(x)$ is a monic irreducible polynomial of degree $m > 1$ over $\mathbb{Z}_p$. Define $l = \sup\{k : p^k | Q(i) \text{ for some } i \in \mathbb{Z}\}$. Then*

$$\nu_p(t_n(Q)) = \sum_{k=1}^{\lfloor l/m \rfloor} m \frac{n}{p^k} + \left(l - m \left\lfloor \frac{l}{m} \right\rfloor \right) \frac{n}{p^{\lfloor l/m \rfloor + 1}} + O(1). \tag{3.4}$$

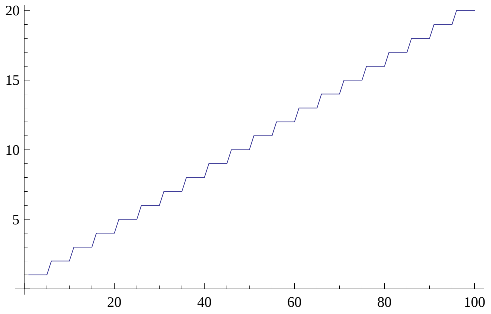

FIGURE 2. The valuation $\nu_5(t_n(\Phi_5))$.

Proof. The compactness of $\mathbb{Z}_p$ shows that $l < \infty$. If not, there is a sequence of integers $\{a_n\}$ such that $Q(a_n) \to 0$ in $\mathbb{Q}_p$. The limit of any convergent subsequence produces a zero of Q in $\mathbb{Z}_p$. This contradicts the irreducibility of $Q(x)$ over $\mathbb{Z}_p$.

Without loss of generality assume $l \geq 1$. Let $n_0 \in \mathbb{Z}$ be such that $p^l | Q(n_0)$. Assume that $\alpha_1, \cdots, \alpha_m$ are the roots of $Q(x)$ in the algebraic closure $\bar{\mathbb{Q}}_p$ of $\mathbb{Q}_p$. The p-adic absolute value on $\mathbb{Q}_p$ can be extended to $\bar{\mathbb{Q}}_p$ and this extension is invariant under Galois transformations over $\mathbb{Q}_p$. Thefore, for $i \in \mathbb{Z}$ we have that $|i - \alpha_j|_p$ is the same for all $j = 1, \cdots, m$. Since $|Q(n_0)|_p = p^{-l}$ we conclude that $|n_0 - \alpha_j|_p = p^{-l/m}$.

Now, assume $|i - n_0|_p = p^{-k}$. If $k \leq l/m$, then it is clear that $|i - \alpha_j|_p = p^{-k}$ and $|Q(i)|_p = p^{-mk}$. This is a direct consequence of the nonarchimedean triangle inequality. On the other hand, if $k > l/m$, then $|Q(i)|_p = p^{-l}$. This is because $|Q(i)|_p \geq p^{-l}$ for any $i \in \mathbb{Z}$. Since

$$\#\{1 \leq i \leq n : |i - n_0|_p = p^{-k}\} = \frac{n}{p^k} - \frac{n}{p^{k+1}} + O(1)$$

and

$$\#\{1 \leq i \leq n : |i - n_0|_p \leq p^{-(\lfloor l/m \rfloor + 1)}\} = \frac{n}{p^{\lfloor l/m \rfloor + 1}} + O(1),$$

we conclude that

$$\begin{aligned} \nu_p(t_n(Q)) &= \sum_{k=1}^{\lfloor l/m \rfloor} mk \frac{n}{p^k} \left(1 - \frac{1}{p}\right) + l \frac{n}{p^{\lfloor l/m \rfloor + 1}} + O(1) \\ &= \sum_{k=1}^{\lfloor l/m \rfloor} m \frac{n}{p^k} + \left(l - m \left\lfloor \frac{l}{m} \right\rfloor\right) \frac{n}{p^{\lfloor l/m \rfloor + 1}} + O(1). \end{aligned} \tag{3.5}$$

Theorem 3.4 has been established. □

Note 3.1. In example 3.3 we have $l = 1$. Therefore (3.4) gives $\nu_p(t_n(\Phi_p)) = n/p + O(1)$, as before. A similar argument shows that, in the case $p = 17$ in example 3.2, we obtain $\nu_{17}(t_n(Q)) = n/17 + O(1)$. This completes the analysis presented in that example.

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