CHARACTERIZING THE 2-ADIC ORDER OF THE LOGARITHM

T. Lengyel
Occidental College, 1600 Campus Road, Los Angeles, CA 90041
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1. Introduction

We define $\nu_p(x)$ as the highest power of prime p which divides the integer x. The function $\nu_p(x)$ is often called the p-adic order of x. In this paper we characterize the divisibility by 2 of the series $\sum_{k=1}^{\infty}(-1)^{k-1}x^k/k$ and $\sum_{k=1}^{\infty}\frac{x^k}{k}$, i. e., we determine their 2-adic orders. The characterization generalizes previously known results on 2-adic orders and is based on elementary proofs.

2. Results

For an integer x, the p-adic order $\nu_p(x)$ of x is the highest power of prime p which divides x. We can think of the relations $p|x$ and $p\not|x$ as $\nu_p(x) \geq 1$ and $\nu_p(x) = 0$, respectively.

We set $\nu_p(0) = \infty$ and $\nu_p(x/y) = \nu_p(x) - \nu_p(y)$ if both x and y are integers. Therefore, for all nonzero rational numbers the order is defined to be a finite integer. From now on all rational numbers will be meant in lowest terms.

For rational numbers $a_k (k \geq 0)$ and rational x, the p-adic order, $\nu_p(\sum_{k=0}^{\infty} a_k x^k)$ of the series $\sum_{k=0}^{\infty} a_k x^k$ can be introduced as $\lim_{n\to\infty} \nu_p(\sum_{k=0}^{n} a_k x^k)$ if the limit exists, in which case there exists an n_0 such that $\nu_p(\sum_{k=0}^{n} a_k x^k) = \nu_p(\sum_{k=0}^{\infty} a_k x^k)$ for $n \geq n_0$. To illustrate this, we consider the series $\frac{x}{1-x} = x + x^2 + x^3 + \ldots$. The reader can easily verify that $\nu_p\left(\frac{x}{1-x}\right) = \nu_p(x)$ if $\nu_p(x) \geq 1$ and the limit does not exist if $\nu_p(x) \leq 0$. Actually, $\nu_p(x + x^2 + x^3 + \ldots + x^n) = n\nu_p(x)$ if $\nu_p(x) < 0$. Notice that if $\nu_2(x) = 0$ then $\nu_2(x + x^2 + x^3 + \ldots + x^{2n+1}) = 0$, while $\nu_2(x + x^2 + x^3 + \ldots + x^{2^n}) \geq n$. Finding the p-adic order of functions helps analyzing the divisibility property of the underlying or related functions. We note that Clarke [1] has recently studied the p-adic order of the logarithm by using p-adic arguments in order to characterize the divisibility properties of the *Stirling* and *partial Stirling numbers*. The interested reader should consult a book on p-adic metrics (e.g, [2]) for a general treatise of p-adic power series.

In this paper we consider the series $\log(1+x) = \sum_{k=1}^{\infty}(-1)^{k-1}x^k/k$ and $-\log(1-x) = \sum_{k=1}^{\infty}\frac{x^k}{k}$ and determine their 2-adic orders by elementary arguments based on binomial expansion.

In most cases the p-adic order of $\log(1+x)$ can be derived by the well-known

Theorem A. (Yu [4]) We have $\nu_p\big(\log(1+x)\big) = \nu_p(\sum_{k=1}^{\infty}(-1)^{k-1}x^k/k) = \nu_p(x)$ if $\nu_p(x) > \frac{1}{p-1}$, and $\nu_p\big(\log(1+x)\big)$ does not exist if $\nu_p(x) \le 0$. In particular, for any integer x, $\nu_p\big(\log(1+x)\big) = \nu_p(x)$ if $p \ge 3$ and $p|x$, or if $p=2$ and $4|x$, while for $p \not| x$ the p-adic order $\nu_p\big(\log(1+x)\big)$ does not exist.

In fact, Theorem A completely describes the p-adic order for $p \ge 3$. The purpose of this paper is to characterize the 2-adic orders of the two series in the case not covered by Theorem A, i. e., for every even integer x and $p=2$. We note that the proof of Theorem A is based on the observation that under the conditions of Theorem A given for p and x, the p-adic order of the terms $(-1)^{k-1}\frac{x^k}{k}$, $k \ge 2$, of the infinite series $\sum_{k=1}^{\infty}(-1)^{k-1}\frac{x^k}{k}$ exceeds that of the first term, x (cf. [2], p. 81).

If $p=2$ and $x=2$ then the following lemma (cf. [2], Exercise 7, p. 83) describes the 2-adic "behavior" of $\sum_{k=1}^{n}\frac{2^k}{k}$, i. e., the sum of the first n terms of the expansion $-\log(1-x)$.

Lemma B. The 2-adic order of the rational number $\sum_{k=1}^{n}\frac{2^k}{k}$ approaches infinity as n increases.

An elementary proof can be given based on the observation that $\nu_2\big(\sum_{k=n+1}^{\infty}\frac{2^k}{k}\big) \ge \min_{k\ge n+1}(k-\nu_2(k))$, which assures that $\nu_2\big(\sum_{k=n+1}^{\infty}\frac{2^k}{k}\big)$ becomes arbitrary large as $n \to \infty$. One can prove that $\nu_2\big(\sum_{k=1}^{n}\frac{2^k}{k}\big) \ge \nu_2\big(\sum_{k=n+1}^{\infty}\frac{2^k}{k}\big)$ holds for infinitely many values n. In fact, a p-adic argument shows that equality holds for all n. We leave the details to the reader.

We set $\nu_p(\sum_{k=0}^{\infty}a_kx^k) = \infty$ if, for every integer $N \ge 1$ there exists an integer n_0 such that p^N divides $\sum_{k=0}^{n}a_kx^k$ for every $n \ge n_0$. In this case $\nu_p(\sum_{k=0}^{n}a_kx^k) = \nu_p(\sum_{k=n+1}^{\infty}a_kx^k)$ holds. By the Lemma, we set $\nu_2\big(\sum_{k=1}^{\infty}\frac{2^k}{k}\big) = \infty$. We note that 0 and 2 play a special role in the 2-adic analysis of $\log(1-x)$ for these are the values for which $\nu_2\big(\log(1-x)\big) = \infty$ ([2]). Our results are summarized in the following two theorems.

Theorem 1. For any even positive integer x,

$$\nu_2\Big(\sum_{k=1}^{\infty}(-1)^{k-1}\frac{x^k}{k}\Big) = \begin{cases} 2, & \text{if } x = 2, \\ 2, & \text{if } x \equiv 2 \pmod{16}, \\ 2, & \text{if } x \equiv 4 \pmod{16}, \\ 3, & \text{if } x \equiv 6 \pmod{16}, \\ 3, & \text{if } x \equiv 8 \pmod{16}, \\ 2, & \text{if } x \equiv 10 \pmod{16}, \\ 2, & \text{if } x \equiv 12 \pmod{16}, \\ \nu_2(x+2), & \text{if } x \equiv 14 \pmod{16}, \\ \nu_2(x), & \text{if } x \equiv 0 \pmod{16}. \end{cases}$$

Theorem 2. For any even positive integer x,

$$\nu_2\Big(\sum_{k=1}^{\infty}\frac{x^k}{k}\Big) = \begin{cases} \infty, & \text{if } x = 2, \\ \nu_2(x-2), & \text{if } x \equiv 2 \pmod{16}, \\ 2, & \text{if } x \equiv 4 \pmod{16}, \\ 2, & \text{if } x \equiv 6 \pmod{16}, \\ 3, & \text{if } x \equiv 8 \pmod{16}, \\ 3, & \text{if } x \equiv 10 \pmod{16}, \\ 2, & \text{if } x \equiv 12 \pmod{16}, \\ 2, & \text{if } x \equiv 14 \pmod{16}, \\ \nu_2(x), & \text{if } x \equiv 0 \pmod{16}. \end{cases}$$

Remark 1. The above theorems could be restated in a more compact form:

$$\nu_2\Big(\sum_{k=1}^{\infty}(-1)^{k-1}\frac{x^k}{k}\Big) = \begin{cases} \nu_2(x), & \text{if } x \equiv 0,\ 4,\ 8,\ 12 \pmod{16}, \\ \nu_2(x+2), & \text{if } x \equiv 2,\ 6,\ 10,\ 14 \pmod{16}, \end{cases}$$

and

$$\nu_2\Big(\sum_{k=1}^{\infty}\frac{x^k}{k}\Big) = \begin{cases} \nu_2(x), & \text{if } x \equiv 0,\ 4,\ 8,\ 12 \pmod{16}, \\ \nu_2(x-2), & \text{if } x \equiv 2,\ 6,\ 10,\ 14 \pmod{16}. \end{cases}$$

Notice the sharp contrast between $\nu_2\big(\sum_{k=1}^{\infty}(-1)^{k-1}2^k/k\big)$ and $\nu_2\big(\sum_{k=1}^{\infty}\frac{2^k}{k}\big)$. We can combine the cases $x \neq 2$ of the two theorems by substituting $-x$ in place of x and carrying out the modular calculations.

For a rational $x = \frac{a}{b}$ with $\nu_2(x) = 1$ and $b > 1$, there exists a sufficiently large integer m such that $\nu_2\big(\log(1+x)\big) < m$. We set $x' = a * b^{-1}$, where b^{-1} is the unique solution to the equation $b * b^{-1} \equiv 1 \pmod{2^m}$ with $0 < b^{-1} < 2^m$. We can proceed to determine $\nu_2\big(\log(1+x')\big)$ by Theorem 1 and observing that $\nu_2\big(\log(1+x)\big) = \nu_2\big(\log(1+x')\big)$. If $x' \not\equiv 14 \pmod{16}$, then $m = 4$ is an appropriate choice. However, if it turns out that the remainder is 14, then one should check whether $\nu_2(x'+2) < m$ and try a larger m if it fails. A similar method works for determining $\nu_2\big(\log(1-x)\big)$, too.

For example, if $x = 6/5$ then $\nu_2\big(\log(1-6/5)\big) = 2$ follows easily with $m = 4$. We use $m = 5$ and have $x' = 6 * 13 \equiv 14 \pmod{16}$ in order to obtain $\nu_2\big(\log(1+6/5)\big) = \nu_2(6 * 13 + 2) = 4$. For $x = 426/555$, we start with $m = 4$. Since $x' = 426 * 3 \equiv 14 \pmod{16}$ and $\nu_2(426 * 3 + 2) = 8$, we note that we need a larger m. By using $m = 10$, we obtain $x' = 426 * 131 \equiv 14 \pmod{16}$ and $\nu_2\big(\log(1+426/555)\big) = \nu_2(426 * 131 + 2) = 9$.

Remark 2. Similarly to the proof of Theorem A, we observe that $\nu_2(2^s) < \nu_2\big((2^s)^k/k\big)$ if $k \geq 2$ and $s \geq 2$. Therefore, $\nu_2\big(\sum_{k=1}^{\infty} \frac{(2^s)^k}{k}\big) = \nu_2\big(\sum_{k=1}^{\infty}(-1)^{k-1}\frac{(2^s)^k}{k}\big) = \nu_2\big(2^s\big) = s$ if $s \geq 2$.

3. Proofs

Proof of Theorem 1. The case of $x = 2$ is easily verified by checking the first couple of terms of $\sum_{k=1}^{\infty}(-1)^{k-1}x^k/k$. Indeed, $\nu_2\big(\sum_{k=1}^{4}(-1)^{k-1}2^k/k\big) = 2$ and $\nu_2\big(2^k/k\big) > 2$ for $k \geq 5$.

If $x = 6$ or 10 then by inspecting the sum of the first few terms we obtain, similarly to the case of $x = 2$, that the orders are 3 and 2, respectively.

We can extend these results for $x \equiv 2, 6,$ and $10 \pmod{16}$. From now on a denotes an arbitrary integer while b is an arbitrary odd integer. The basic idea is that if $\nu_2\big(\sum_{k=1}^{\infty}(-1)^{k-1}\frac{x^k}{k}\big) = r < s$ then $\nu_2\big(\sum_{k=1}^{\infty}(-1)^{k-1}\frac{(x+a2^s)^k}{k}\big) = r$ too, since $x^k \equiv (x + a2^s)^k \pmod{2^s}$. [Of course, the same applies if we omit the factors $(-1)^{k-1}$.] By the previous observations, we can set $s = 4$.

For $x \equiv 0, 4, 8$ or $12 \pmod{16}$ the statement follows from Theorem A which claims that the order must be $\nu_2(x)$.

Instead of simply proving the remaining case $x \equiv 14 \pmod{16}$, we combine the cases $x \equiv 2$ and $14 \pmod{16}$ to make this proof transparent to prove Theorem 2. Let $s = 4$. We calculate the 2-adic order of $\sum_{k=1}^{\infty}(-1)^{k-1}x^k/k$ using the binomial expansion of the terms $x^k = (b2^s + 2c)^k$ where c is either 1 or -1. The expansion yields

$$(b2^s + 2c)^k = \Big(2\,(b2^{s-1} + c)\Big)^k = \sum_{l=0}^{k} 2^k \binom{k}{l} (b2^{s-1})^l c^{k-l}.$$

Note that the identity $\binom{k}{l} = \frac{k}{l}\binom{k-1}{l-1}$ implies that $\binom{k}{l}/k$ is an integer multiple of $1/l$. Consider the sum $\sum_{k=1}^{\infty}(-1)^{k-1}\frac{(b2^s+2c)^k}{k}$ in three terms, one term for $l = 0$, another for $l = 1$, and the last one for all the remaining cases, $l \geq 2$. We get

$$\begin{aligned}
&\sum_{k=1}^{\infty}(-1)^{k-1}\frac{(b2^s + 2c)^k}{k} = \\
(1)\qquad &= -\sum_{k=1}^{\infty}\frac{(-2c)^k}{k} + \sum_{k=1}^{\infty} b2^{k+s-1}(-c)^{k-1} + \\
&+ \sum_{k=1}^{\infty}(-1)^{k-1}\sum_{l=2}^{k}\frac{\binom{k-1}{l-1} b^l 2^{l(s-1)+k} c^{k-l}}{l}.
\end{aligned}$$

Obviously, the 2-adic order of the second term is s if $b \neq 0$. Notice that the third term is always divisible by 2^{s+1} for $s \geq 3$, since this condition implies that $l(s-1)+k-\nu_2(l) \geq l(s-1)+k-\log_2 l \geq s+1$. It turns out that the 2-adic order of the first term on the right side of identity (1) is 2 if $c=1$ as we have seen it at the beginning of the proof. By Lemma B, the 2-adic order of the first term is ∞ if $c=-1$. It follows that $\nu_2\big(\sum_{k=1}^{\infty}(-1)^{k-1}(b2^s+2c)^k/k\big)=s$ if $c=-1$ (and $b \neq 0$), while it is 2 if $c=1$. ∎

Proof of Theorem 2. Basically, the proof of Theorem 1 can be repeated here except for $x=2$, which case is the content of Lemma B. Careful inspection reveals that the 2-adic orders are switched for $x \equiv 6$ and $10 \pmod{16}$.

Similarly to identity (1), we have

$$\sum_{k=1}^{\infty}\frac{(b2^s+2c)^k}{k}=\sum_{k=1}^{\infty}\frac{(2c)^k}{k}+ \\ +\sum_{k=1}^{\infty}b2^{k+s-1}c^{k-1}+\sum_{k=1}^{\infty}\sum_{l=2}^{k}\frac{\binom{k-1}{l-1}b^l 2^{l(s-1)+k}c^{k-l}}{l} \tag{2}$$

where the last term is always divisible by 2^{s+1} for $s \geq 3$.

By simply switching the cases $c=1$ and $c=-1$ in the previous proof and using identity (2), we derive that $\nu_2\big(\sum_{k=1}^{\infty}\frac{(b2^s+2c)^k}{k}\big)=s$ if $c=1$ (and $b \neq 0$), while it is 2 if $c=-1$. ∎

We note that Clarke [1] has recently proved similar results by using p-adic arguments.

Lemma B points to the odd behavior of $\nu_2\big(\sum_{k=1}^{n}\frac{x^k}{k}\big)$ at $x=2$. Analysis of this behavior gives rise to the question on the rate at which $\nu_2\big(\sum_{k=1}^{n}\frac{2^k}{k}\big)$ increases as n gets larger. We were unable to answer this question; however, numerical evidence suggests some pattern for the increase of the 2-adic order. The following conjecture has been proposed in [3], in the context of the divisibility by 2 of the Stirling numbers of the second kind, $S(a2^n-1, 2^m)$ where $n > m \geq 4$ and a is a positive integer.

Conjecture 3. For $m \geq 4$, $\nu_2\big(\sum_{k=1}^{2^m}\frac{2^k}{k}\big)=2^m+2m-2$.

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