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PRACTICAL NUMBERS IN LUCAS SEQUENCES

CARLO SANNA

ABSTRACT. A practical number is a positive integer n such that all the positive integers $m \leq n$ can be written as a sum of distinct divisors of n. Let $(u_n)_{n\geq 0}$ be the Lucas sequence satisfying $u_0 = 0, u_1 = 1$, and $u_{n+2} = au_{n+1} + bu_n$ for all integers $n \geq 0$, where a and b are fixed nonzero integers. Assume a(b+1) even and $a^2 + 4b > 0$. Also, let \mathcal{A} be the set of all positive integers n such that $|u_n|$ is a practical number. Melfi proved that \mathcal{A} is infinite. We improve this result by showing that $\#\mathcal{A}(x) \gg x/\log x$ for all $x \geq 2$, where the implied constant depends on aand b. We also pose some open questions regarding \mathcal{A} .

1. INTRODUCTION

A practical number is a positive integer n such that all the positive integers $m \leq n$ can be written as a sum of distinct divisors of n. The term "practical" was coined by Srinivasan [7]. Let \mathcal{P} be the set of practical numbers. Estimates for the counting function $\#\mathcal{P}(x)$ were given by Hausman and Shapiro [1], Tenenbaum [10], Margenstern [2], Saias [5], and, finally, Weingartner [12], who proved that there exists a constant C > 0 such that

$$\#\mathcal{P}(x) = \frac{Cx}{\log x} \cdot \left(1 + O\left(\frac{\log\log x}{\log x}\right)\right)$$

for all $x \geq 3$, settling a conjecture of Margenstern [2].

In analogy with well-known conjectures about prime numbers, Melfi [4] proved that every positive even integer is the sum of two practical numbers, and that there are infinitely many triples (n, n + 2, n + 4) of practical numbers. Let $(u_n)_{n\geq 0}$ be a Lucas sequence, that is, a sequence of integers satisfying $u_0 = 0$, $u_1 = 1$, and $u_{n+2} = au_{n+1} + bu_n$ for all integers $n \geq 0$, where a and b are two fixed nonzero integers. Also, let \mathcal{A} be the set of all positive integers n such that $|u_n|$ is a practical number. From now on, we assume $a^2 + 4b > 0$ and a(b+1) even. We remark that, in the study of \mathcal{A} , assuming a(b+1) even is not a loss of generality. Indeed, if a(b+1) is odd then u_n is odd for all $n \geq 1$ and, since 1 is the only odd practical number, it follows that $\mathcal{A} = \{1\}$. Melfi [3, Theorem 10] proved the following result.

Theorem 1.1. The set \mathcal{A} is infinite. Precisely, $2^j \cdot 3 \in \mathcal{A}$ for all sufficiently large positive integers j, how large depending on a and b, and hence

$$\#\mathcal{A}(x) \gg \log x,$$

for all sufficiently large x > 1.

In this paper, we improve Theorem 1.1 to the following:

Theorem 1.2. For all $x \ge 2$, we have

$$\#\mathcal{A}(x) \gg \frac{x}{\log x}$$

where the implied constant depends on a and b.

We leave the following open questions to the interested readers:

- (Q1) Does \mathcal{A} have zero natural density?
- (Q2) Can a nontrivial upper bound for $\#\mathcal{A}(x)$ be proved?

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- (Q3) Are there infinitely many nonpractical n such that $|u_n|$ is practical?
- (Q4) Are there infinitely many practical n such that $|u_n|$ is nonpractical?
- (Q5) What about practical numbers in general integral linear recurrences over the integers?

Notation. For any set of positive integers S, we put $S(x) := S \cap [1, x]$ for all $x \ge 1$, and #S(x) denotes the counting function of S. We employ the Landau–Bachmann "Big Oh" notation O, as well as the associated Vinogradov symbols \ll and \gg , with their usual meanings. Any dependence of the implied constants is explicitly stated. As usual, we write $\mu(n)$, $\varphi(n)$, $\sigma(n)$, and $\omega(n)$, for the Möbius function, the Euler's totient function, the sum of divisors, and the number of prime factors of a positive integer n, respectively.

2. Preliminaries on Lucas sequences

In this section we collect some basic facts about Lucas sequences. Let α and β be the two roots of the characteristic polynomial $X^2 - aX - b$. Since $a^2 + 4b > 0$ and $b \neq 0$, we have that α and β are real, nonzero, and distinct. It is well known that the generalized Binet's formula

(1)
$$u_n = \frac{\alpha^n - \beta^n}{\alpha - \beta}$$

holds for all integers $n \ge 0$. Define

$$\Phi_n := \prod_{\substack{1 \le k \le n \\ \gcd(n,k) = 1}} \left(\alpha - e^{2\pi \mathbf{i}k/n} \beta \right),$$

for each positive integer n. It can be proved that $\Phi_n \in \mathbb{Z}$ for all integers n > 1 (see, e.g., [9, p. 428]). Furthermore, we have

(2)
$$u_n = \prod_{\substack{d \mid n \\ d > 1}} \Phi_d$$

and, by the Möbius inversion formula,

(3)
$$\Phi_n = \prod_{d \mid n} u_{n/d}^{\mu(d)}$$

for all integers n > 1. Changing the sign of a changes the signs of α, β and turns u_n into $(-1)^{n+1}u_n$, which is not a problem, since for the study of \mathcal{A} we are interested only in $|u_n|$. Hence, without loss of generality, we can assume a > 0 and $\alpha > |\beta|$, which in turn implies that $u_n, \Phi_n > 0$ for all integers n > 0. We conclude this section with an easy lemma regarding the growth of u_n and Φ_n .

Lemma 2.1. For all integers n > 0, we have

(i)
$$u_n \ge u_{n-1};$$

(ii) $u_n = \alpha^{n+O(1)};$
(iii) $\Phi_n = \alpha^{\varphi(n)+O(1)};$

where the implied constants depend on a and b.

Proof. If b > 0, then (i) is clear from the recursion for u_n . Hence, suppose b < 0, so that $\beta > 0$. After a bit of manipulations, (i) is equivalent to $\alpha^{n-1}(\alpha - 1) \ge \beta^{n-1}(\beta - 1)$, which in turn follows easily since $\alpha > \beta > 0$. Claim (ii) is a consequence of (1). Setting $\gamma := \beta/\alpha$, by (1) and (3), we get

$$\Phi_n = \alpha^{\varphi(n)} \prod_{d \mid n} \left(\frac{1 - \gamma^{n/d}}{\alpha - \beta} \right)^{\mu(d)} = \alpha^{\varphi(n)} \prod_{d \mid n} \left(1 - \gamma^{n/d} \right)^{\mu(d)},$$

for all integers n > 1, where we used the well-known formulas $\sum_{d \mid n} \mu(d) \frac{n}{d} = \varphi(n)$ and $\sum_{d \mid n} \mu(d) = 0$. Therefore, since $|\gamma| < 1$, we have

$$|\log(\Phi_n/\alpha^{\varphi(n)})| \le \sum_{d \mid n} |\log(1-\gamma^d)| \ll \sum_{d=1}^{\infty} |\gamma|^d \ll 1,$$

and also (iii) is proved.

3. Preliminaries on practical numbers and close relatives

The following lemma on practical numbers will be fundamental later.

Lemma 3.1. If n is a practical number and $m \leq 2n$ is a positive integer, then mn is a practical number.

Proof. See [4, Lemma 1].

Close relatives of practical numbers are φ -practical numbers. A φ -practical number is a positive integer n such that all the positive integers $m \leq n$ can be written as $m = \sum_{d \in \mathcal{D}} \varphi(d)$, where \mathcal{D} is a subset of the divisors of n. This notion was introduced by Thompson [11] while studying the degrees of the divisors of the polynomial $X^n - 1$. Indeed, φ -practical numbers are exactly the positive integers n such that $X^n - 1$ has a divisor of every degree up to n.

We need a couple of results regarding $\varphi\text{-}\mathrm{practical}$ numbers.

Lemma 3.2. Let n be a φ -practical number and p be a prime number not dividing n. Then pn is φ -practical if and only if $p \le n+2$. Moreover, $p^j n$ is φ -practical if and only if $p \le n+1$, for every integer $j \ge 2$.

Proof. See [11, Lemma 4.1].

Lemma 3.3. If n is an even φ -practical number, and if d_1, \ldots, d_s are all the divisors of n ordered so that $\varphi(d_1) \leq \cdots \leq \varphi(d_s)$, then

(4)
$$\varphi(d_{j+1}) \le \sum_{i=1}^{j} \varphi(d_i),$$

for all positive integers j < s.

Proof. It is not difficult to see that n is φ -practical if and only if

(5)
$$\varphi(d_{j+1}) \le 1 + \sum_{i=1}^{j} \varphi(d_i)$$

for all positive integers j < s (see [11, p. 1041]). Hence, we have only to prove that n even ensures that in (5) the equality cannot happen. If j = 1 then (4) is obvious since $\{d_1, d_2\} = \{1, 2\}$, so we can assume 1 < j < s. At this point $\varphi(d_{j+1})$ is even, while

$$1 + \sum_{i=1}^{j} \varphi(d_i)$$

is odd, because $\varphi(m)$ is even for all integers m > 2. Thus, in (5) the equality is not satisfied. \Box

Let θ be a real-valued arithmetic function, and define \mathcal{B}_{θ} as the set containing n = 1 and all those $n = p_1^{a_1} \cdots p_k^{a_k}$, where $p_1 < \cdots < p_k$ are prime numbers and a_1, \ldots, a_k are positive integers, which satisfy

$$p_j \le \theta\left(\prod_{i=1}^{j-1} p_i^{a_i}\right),$$

for j = 1, ..., k, where the empty product is equal to 1. If $\theta(n) := \sigma(n) + 1$, then \mathcal{B}_{θ} is the set of practical numbers. This is a characterization given by Stewart [8] and Sierpiński [6].

 \square

Weingartner proved a general and strong estimate for $\#\mathcal{B}_{\theta}(x)$. The following is a simplified version adapted just for our purposes.

Theorem 3.4. Suppose $\theta(1) \ge 2$ and $n \le \theta(n) \le An$ for all positive integers n, where $A \ge 1$ is a constant. Then, we have

$$#\mathcal{B}_{\theta}(x) \sim \frac{c_{\theta}x}{\log x},$$

as $x \to +\infty$, where $c_{\theta} > 0$ is a constant.

Proof. See [12, Theorems 1.2 and 5.1].

4. Proof of Theorem 1.2

The key tool of the proof is the following technical lemma.

Lemma 4.1. Suppose that n is a sufficiently large positive integer, how large depending on a and b. Let p be a prime number and write $n = p^v m$ for some nonnegative integer v and some positive integer m not divisible by p. If m is an even φ -practical number, $n \in A$, and p < m, then $p^k n \in A$ for all positive integers k.

Proof. Clearly, it is enough to prove the claim for k = 1. Let $d_1 = 1, d_2 = 2, \ldots, d_s$ be all the divisors of m, ordered to that $\varphi(d_1) \leq \cdots \leq \varphi(d_s)$. Furthermore, define

$$N_j := u_n \prod_{i=1}^j \Phi_{p^{\nu+1}d_i},$$

for j = 1, ..., s. We shall prove that each N_j is practical. This implies the thesis, since $N_s = u_{pn}$ by (2).

We proceed by induction on j. First, by (2) and Lemma 2.1(i), we have

$$\Phi_{p^{v+1}d_1} = \Phi_{p^{v+1}} \le u_{p^{v+1}} \le u_{p^v m} = u_n,$$

since p < m. Hence, applying Lemma 3.1 and the fact that u_n is practical, we get that $N_1 = u_n \Phi_{p^{\nu+1}d_1}$ is practical.

Now assuming that N_j is practical we shall prove that N_{j+1} is practical. Again, since $N_{j+1} = \Phi_{p^{\nu+1}d_{j+1}}N_j$, thanks to Lemma 3.1 it is enough to show that the inequality

(6)
$$\Phi_{p^{\nu+1}d_{j+1}} \le u_n \prod_{i=1}^{j} \Phi_{p^{\nu+1}d}$$

holds. In turn, by Lemma 2.1(ii) and (iii), we have that (6) is implied by

(7)
$$n + \varphi(p^{\nu+1}) \left[-\varphi(d_{j+1}) + \sum_{i=1}^{j} \varphi(d_i) \right] \ge C(j+1)$$

where C > 0 is a constant depending only on a and b.

On the one hand, since m is an even φ -practical number, by Lemma 3.3 we have that the term of (7) in square brackets is nonnegative. On the other hand, for sufficiently large n, we have

$$n \ge C(\log n / \log 2 + 1) \ge C(\omega(n) + 1) \ge C(j+1)$$

Therefore, (7) holds and the proof is complete.

We are ready to prove Theorem 1.2. Pick a sufficiently large positive integer h, depending on a and b, such that the claim of Lemma 4.1 holds for all integers $n \ge 2^h \cdot 3$. Moreover, by Theorem 1.1, we can assume that $2^j \cdot 3 \in \mathcal{A}$ for all integers $j \ge h$. Put $\mathcal{B} := \mathcal{B}_{\theta} \setminus \{1\}$, where $\theta(n) := \max\{2, n\}$. Note that, as a consequence of Lemma 3.2, all the elements of \mathcal{B} are even φ -practical numbers. We shall prove that for all $n \in \mathcal{B}$ we have $2^h \cdot 3n \in \mathcal{A}$. In this way, thanks to Theorem 3.4, we get

$$#\mathcal{A}(x) \ge #\mathcal{B}\left(\frac{x}{2^h \cdot 3}\right) \gg \frac{x}{\log x},$$

for all sufficiently large x. Hence, since $1 \in \mathcal{A}$, Theorem 1.2 follows.

We proceed by induction on the number of prime factors of $n \in \mathcal{B}$. If $n \in \mathcal{B}$ has exactly one prime factor, then it follows easily that $n = 2^j$ for some positive integer j. Hence, we have $2^h \cdot 3n = 2^{h+j} \cdot 3 \in \mathcal{A}$, as claimed.

Now, assuming that the claim is true for all $n \in \mathcal{B}$ with exactly $k \geq 1$ prime factors, we shall prove it for all $n \in \mathcal{B}$ having k+1 prime factors. Write $n = p_1^{a_1} \cdots p_{k+1}^{a_{k+1}}$, where $p_1 < \cdots < p_{k+1}$ are prime numbers and a_1, \ldots, a_{k+1} are positive integers. Put also $m := p_1^{a_1} \cdots p_k^{a_k}$. Since $n \in \mathcal{B}$, we have $m \in \mathcal{B}$ and $p_{k+1} < m$. On the one hand, by the induction hypothesis, $2^h \cdot 3m \in \mathcal{A}$. On the other hand, it is easy to see that $m \in \mathcal{B}$ implies $2^h m \in \mathcal{B}$ and $2^h \cdot 3m \in \mathcal{B}$.

First, suppose $p_{k+1} > 3$. Since $2^h \cdot 3m$ is an even φ -practical number, $2^h \cdot 3m \in \mathcal{A}$, and $p_{k+1} < 2^h \cdot 3m$, by Lemma 4.1 we get that $2^h \cdot 3n = 2^h \cdot 3mp_{k+1}^{a_{k+1}} \in \mathcal{A}$, as claimed.

On the other hand, if $p_{k+1} = 3$ the situation is similar. Since $2^h m$ is an even φ -practical number, $2^h \cdot 3m \in \mathcal{A}$, and $p_{k+1} < 2^h m$, by Lemma 4.1 we get that $2^h \cdot 3n = 2^h \cdot 3m p_{k+1}^{a_{k+1}} \in \mathcal{A}$, as claimed. The proof is complete.

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