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GAPS IN BINARY EXPANSIONS OF SOME ARITHMETIC FUNCTIONS AND THE IRRATIONALITY OF THE EULER CONSTANT

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Abstract. We show that if $F_n = 2^{2^n} + 1$ is the nth Fermat number, then the binary digit sum of $\pi(F_n)$ tends to infinity with n, where $\pi(x)$ is the counting function of the primes $p \leq x$. We also show that if F_n is not prime, then the binary expansion of $\phi(F_n)$ starts with a long string of 1's, where ϕ is the Euler function. We also consider the binary expansion of the counting function of irreducible monic polynomials of degree a given power of 2 over the field $\mathbb{F}_2$. Finally, we relate the problem of the irrationality of Euler constant with the binary expansion of the sum of the divisor function.

Key words: binary expansions, prime number theorem, rational approximations to $\log 2$, Fermat numbers, Euler constant, irreducible polynomials over a finite field.
AMS subject: 11A63, 11D75, 11N05.

1. Fermat Numbers

1.1. **The prime counting function.** Let $F_n = 2^{2^n} + 1$ be the nth Fermat number. In 1650, Fermat conjectured that all the numbers F_n are prime. However, to date it is known that F_n is prime for $n \in \{0, 1, 2, 3, 4\}$ and for no other n in the set $\{5, 6, \ldots, 32\}$. It is believed that F_n is composite for all $n \geq 5$. For more information on Fermat numbers, see [3].

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For a positive real number x we put $\pi(x) = \#\{p \le x\}$ for the counting function of the primes $p \le x$. Consider the sequence $P_n = \pi(F_n)$ for all $n \ge 0$. Observe that F_n is prime if and only if $\pi(F_n) > \pi(F_n - 1)$.

Here, we look at the binary expansion of P_n. In particular, we prove that P_n cannot have few bits in its binary expansion. To quantify our result, let $s_2(P_n)$ be the binary sum of digits of P_n.

Theorem 1. *There exists a constant c_0 such that the inequality*

$$s_2(P_n) > \frac{\log n}{2\log 2} - c_0$$

holds for all $n \ge 0$.

Before proving the theorem we need a preliminary lemma. Let

$$\begin{aligned}(\log 2)^{-1} &= 2^0 + 2^{-2} + 2^{-3} + 2^{-4} + 2^{-8} + \cdots + 2^{-a_k} + \cdots \\ 2 - (\log 2)^{-1} &= 2^{-1} + 2^{-5} + 2^{-6} + 2^{-7} + 2^{-9} + \cdots + 2^{-b_k} + \cdots\end{aligned}$$

where $\mathcal{A} = \{a_k\}_{k\ge 0}$ is the sequence $(0, 2, 3, 4, 8, \ldots)$ giving the position of the kth bit in the binary expansion of $(\log 2)^{-1}$, and $\mathcal{B} = \{b_k\}_{k\ge 0}$ is the sequence $(1, 5, 6, 7, 9, \ldots)$ giving the position of the kth zero coefficient in the binary expansion of $2 - (\log 2)^{-1}$. These sequences are disjoint and their union is the sequence of nonnegative integers.

Lemma 2. *There exist k_0 such that for any $k \ge k_0$ we have $a_{k+1} < 4a_k$ and $b_{k+1} < 4b_k$.*

Proof. By definition

$$(\log 2)^{-1} = \sum_{i=0}^{k} 2^{-a_i} + M,$$

where $M < 2^{-a_{k+1}+1}$. We use the fact (see below) that there exists a constant K such that

$$\left|\frac{1}{\log 2} - \frac{p}{q}\right| > \frac{1}{q^K} \tag{1}$$

holds for all positive rational numbers p/q. We take $q = 2^{a_k}$ and $p = \sum_{i=0}^{k} 2^{a_k - a_i}$, to get

$$\frac{1}{2^{a_{k+1}-1}} = \sum_{m \ge a_{k+1}} \frac{1}{2^m} > \frac{1}{\log 2} - \frac{p}{q} > \frac{1}{2^{Ka_k}},$$

so

$$a_{k+1} < Ka_k + 1 \quad \text{for all} \quad k \ge 0.$$

It is known that we can take $K = 3.58$ for k sufficiently large, say $k \ge k_0$ (see [4]; see also [8] for the fact that we can take $K = 3.9$ for $k \ge k_0$). The result for a_k now follows trivially. The exact same reasoning, substituting $1/\log 2$ by $2 - 1/\log 2$ everywhere, gives the result for b_k. □

Corollary 3. *For each integer n let $\kappa_0 := \kappa_0(n)$ be the largest positive integer k such that $b_k < n-3$ and $\kappa_1 := \kappa_1(n)$ be the largest positive integer k such that $a_k < b_{\kappa_0}$. Then the inequalities $b_{\kappa_0} \geq (n-3)/4$ and $a_{\kappa_1} \geq (n-3)/16$ hold for all sufficiently large n.*

Proof. We have

$$a_{\kappa_1} < b_{\kappa_0} < n - 3 \leq b_{\kappa_0+1} < 4b_{\kappa_0}$$

and

$$b_{\kappa_0} < a_{\kappa_1+1} < 4a_{\kappa_1}.$$

□

We now start the proof of theorem 1.1.

Proof. Assume now that $n \geq 4$. By Theorem 1 in [7], we have

$$\frac{x}{\log x}\left(1 + \frac{1}{2\log x}\right) < \pi(x) < \frac{x}{\log x}\left(1 + \frac{3}{2\log x}\right) \qquad \text{for all} \qquad x \geq 59. \tag{2}$$

Since $F_n \geq F_4 > 59$, we may apply inequality (2) with $x = F_n$. Since both functions $x \mapsto x/\log x$ and $x \mapsto x/(\log x)^2$ are increasing for $x > e^2$, and $F_n > 2^{2^n} > e^2$ for $n \geq 4$, we have that

$$\pi(F_n) \geq \frac{2^{2^n-n}}{\log 2}\left(1 + \frac{1}{2^{n+1}\log 2}\right) > 2^{2^n-n}\left(\frac{1}{\log 2} + \frac{1}{2^{n+1}}\right),$$

where we used the fact that $1/2 < \log 2 < 1$. Further,

$$\begin{aligned}
\pi(F_n) &\leq \frac{F_n}{\log F_n}\left(1 + \frac{3}{2\log F_n}\right) \\
&< \frac{2^{2^n-n}}{\log 2}\left(1 + \frac{3}{2^{n+1}\log 2}\right)\left(1 + \frac{1}{2^{2^n}}\right) \\
&< \frac{2^{2^n-n}}{\log 2}\left(1 + \frac{3}{2^n} + \frac{1}{2^{2^n}} + \frac{3}{2^{2^n+n}}\right) \\
&< \frac{2^{2^n-n}}{\log 2}\left(1 + \frac{1}{2^{n-2}}\right) \\
&< 2^{2^n-n}\left(\frac{1}{\log 2} + \frac{1}{2^{n-3}}\right).
\end{aligned}$$

Hence,

$$P_n = 2^{2^n-n}\left(\frac{1}{\log 2} + \theta_n\right), \qquad \text{where} \qquad \theta_n \in \left(\frac{1}{2^{n+1}}, \frac{1}{2^{n-3}}\right).$$

Thus, the binary digits of P_n are the same as the binary digits of the number $(\log 2)^{-1} + \theta_n$ and, in fact, the first binary digits of P_n are exactly the a_k for all $k \le \kappa_1$ since $a_{\kappa_1} < b_{\kappa_0}$ and, hence, θ_n does not induce a carry over a_{κ_1}. Applying Lemma 2, iteratively, we get that $a_k \le 4^{k-k_0} a_{k_0}$ for all $k \ge k_0$. Hence,

$$s_2(P_n) > \sum_{j \le \kappa_1, a_j \in \mathcal{A}} 1 = \kappa_1 \ge \frac{\log a_{\kappa_1}/a_{k_0}}{\log 4} + k_0 > \frac{\log n}{\log 4} - c_0,$$

by Corollary 3. □

1.2. **The Euler function.** Let $\phi(n)$ be the Euler function of n. If F_n is prime, then $\phi(F_n) = 2^{2^n}$. We show that if F_n is not prime, then the binary expansion of $\phi(F_n)$ starts with a long string of 1's. More precisely, we have the following result.

Theorem 4. *If F_n is not prime, then the binary expansion of $\phi(F_n)$ starts with a string of 1's of length at least $n - \lfloor \log n / \log 2 \rfloor - 1$.*

We need the following well known lemma (see Proposition 3.2 and Theorem 6.1 in [3]).

Lemma 5. *Any two Fermat numbers are coprime. Further, for $n \ge 2$, each prime factor of F_n is congruent to 1 modulo 2^{n+2}.*

Proof. Let $n \ge 0$ and let p be a prime factor of F_n. Since 2^{2^n} is congruent to -1 modulo p, the order of the class of 2 in the multiplicative group $(\mathbb{Z}/p\mathbb{Z})^\times$ is 2^{n+1}. This shows that two Fermat numbers have no common prime divisor.

Assume now $n \ge 2$. Then p is congruent to 1 modulo 8, hence 2 is a square modulo p. Let a satisfy $a^2 \equiv 2 \pmod{p}$. Then the order of the class of a in the multiplicative group $(\mathbb{Z}/p\mathbb{Z})^\times$ is 2^{n+2} and therefore 2^{n+2} divides $p-1$. □

Proof of Theorem 4. Assume that F_n is not prime. Then $n \ge 5$. Write $F_n = \prod_{i=1}^k p_i^{\alpha_i}$, where $p_1 < \cdots < p_k$ are distinct primes and $\alpha_1, \ldots, \alpha_k$ are positive integer exponents. Using Lemma 5, we can write $p_i = 2^{n+2} m_i + 1$ for each $i = 1, \ldots, k$. Further, no m_i is a power of 2, for otherwise p_i itself would be a Fermat prime, which is false because any two Fermat numbers are coprime by Lemma 5. Let $\mathcal{P}$ be the set of primes $p \equiv 1 \pmod{2^{n+2}}$ which are not Fermat primes and for any positive real number x let $\mathcal{P}(x) = \mathcal{P} \cap [1, x]$. Then $p_i \in \mathcal{P}(2^{2^n})$. Thus,

$$\sum_{i=1}^k \frac{1}{p_i} \le \sum_{\substack{2^{n+2}\cdot 3 \le p \le 2^{2^n} \\ p \in \mathcal{P}}} \frac{1}{p} = \frac{\#\mathcal{P}(t)}{t}\Big|_{t=2^{n+2}\cdot 3}^{t=2^{2^n}} + \int_{2^{n+2}\cdot 3}^{2^{2^n}} \frac{\#\mathcal{P}(t)}{t^2} dt,$$

where the above equality follows from the Abel summation formula. In order to estimate the first term and the integral, we use the fact that

$$\#\mathcal{P}(t) \le \pi(t,1,2^{n+2}) \le \frac{2t}{\phi(2^{n+2})\log(t/2^{n+2})} \quad \text{forall} \quad t \ge 2^{n+2}\cdot 3,$$

where $\pi(t;a,b)$ is the number of primes $p \le t$ in the arithmetic progression $a \pmod b$. The right–most inequality is due to Montgomery and Vaughan [5]. Thus,

$$\begin{aligned}
\sum_{i=1}^{k}\frac{1}{p_i} &\le \frac{\#\mathcal{P}(2^{2^n})}{2^{2^n}} + \int_{2^{n+2}\cdot 3}^{2^{2^n}} \frac{\#\mathcal{P}(t)}{t^2}dt \\
&\le \frac{1}{2^n\log(2^{2^n-n-2})} + \frac{1}{2^n}\int_{2^{n+2}\cdot 3}^{2^{2^n}} \frac{dt}{t\log(t/2^{n+2})} \\
&< \frac{1}{2^n} + \frac{1}{2^n}\int_{3}^{2^{2^n-n-2}} \frac{du}{u\log u} \qquad (u := t/2^{n+2}) \\
&= \frac{1}{2^n} + \frac{\log\log u}{2^n}\Big|_{u=3}^{u=2^{2^n-n-2}} < \frac{1}{2^n} + \frac{\log((2^n-n-2)\log 2)}{2^n} < \frac{n}{2^n}.
\end{aligned}$$

Using the inequality

$$1 - \prod_{i=1}^{k}(1-x_i) < \sum_{i=1}^{k} x_i$$

valid for all $k \ge 1$ and $x_1,\ldots,x_k \in (0,1)$ with $x_i = 1/p_i$ for $i = 1,\ldots,k$, we get

$$1 - \frac{\phi(F_n)}{F_n} = 1 - \prod_{i=1}^{k}\left(1 - \frac{1}{p_i}\right) < \sum_{i=1}^{k}\frac{1}{p_i} < \frac{n}{2^n},$$

therefore

$$\phi(F_n) > F_n\left(1 - \frac{n}{2^n}\right) > 2^{2^n}\left(1 - \frac{n}{2^n}\right),$$

which together with the fact that $\phi(F_n) < F_n - 1 = 2^{2^n}$ (since F_n is composite) implies the desired conclusion. □

2. Digits of the Number of Irreducible Polynomials of a Given Degree over a Finite Field

Let $\mathbb{F}_q$ be a finite field with q elements. For any positive integer m, denote by $N_q(m)$ the number of monic irreducible polynomials over $\mathbb{F}_q$ of degree m. Then (see for instance §14.3 of [1]) for each $m \ge 1$, we have

$$q^m = \sum_{d|m} dN_q(d) \quad \text{and} \quad N_q(m) = \frac{1}{m}\sum_{d|m}\mu(d)q^{m/d}.$$

The two formulae are equivalent by Möbius inversion formula. From the first one, given the fact that all the elements in the sum are positive, we deduce

$$N_q(m) < \frac{q^m}{m} \quad \text{for } m \geq 2.$$

A consequence of the second one is

$$q^m - mN_q(m) = -\sum_{d|m, d<m} \mu(d) q^{d/m} \leq q^{m/2} + \sum_{d \leq m/3} q^d < 2q^{m/2} \quad \text{for } m \geq 2.$$

Hence, we have

$$\frac{q^m}{m} - \frac{2q^{m/2}}{m} < N_q(m) < \frac{q^m}{m}\cdot$$

For $q = 2$ and $m = 2^n$ we deduce that the number $\tilde{P}_n := N_2(2^n)$ satisfies

$$2^{2^n - n} - 2^{2^{n-1} - n + 1} < \tilde{P}_n < 2^{2^n - n}.$$

It follows that the binary expansion of $\tilde{P}_n$ starts with a number of 1's at least $2^{n-1} - 1$.

3. Irrationality of the Euler Constant

Let $T_k = \sum_{n \leq 2^k} \tau(n)$ with $\tau(n) = \sum_{d|n} 1$ and let $T_k = \sum_{i=0}^{v_k} a_i 2^i$ be its binary expansion. If we have $a_{\ell+i} = 0$, for any $0 \leq i \leq L - 1$, we say that T_k has a *gap of length at least L starting at ℓ.*

We introduce the following condition depending on a parameter $\kappa > 0$ and involving Euler's constant γ.

Assumption (A_κ): *There exists a positive constant B_0 with the following property. For any $(b_0, b_1, b_2) \in \mathbb{Z}^3$ with $b_1 \neq 0$, we have*

$$|b_0 + b_1 \log 2 + b_2 \gamma| \geq B^{-\kappa}$$

with

$$B = \max\{B_0,\ |b_0|,\ |b_1|,\ |b_2|\}.$$

From Dirichlet's box principle (see [9]), it follows that if condition (A_κ) is satisfied, then $\kappa \geq 2$. According to (1), condition (A_κ) is satisfied with $\kappa = 3$ if Euler's constant γ is rational. It is likely that it is also satisfied if γ is irrational, but this is an open problem. A folklore conjecture is that $1, \log 2$ and γ are linearly independent over $\mathbb{Q}$. If this is true, then (A_κ) can be seen as a measure of linear independence of these three numbers. It is known (see [9]) that for almost all tuples $(x_1, \ldots, x_m)$ in $\mathbb{R}^m$ in the sense of Lebesgue's measure, the following measure of linear independence holds:

For any $\kappa > m$, there exists a positive constant B_0 such that, for any $(b_0, b_1, \ldots, b_m) \in \mathbb{Z}^{m+1} \setminus \{0\}$, we have

$$|b_0 + b_1 x_1 + \cdots + b_m x_m| \geq B^{-\kappa}$$

with

$$B = \max\{B_0,\ |b_0|,\ |b_1|, \ldots,\ |b_m|\}.$$

It is also expected that *most* constants from analysis, like $\log 2$ and γ, behave, from the above point of view, as almost all numbers. Hence, one should expect condition (A_κ) to be satisfied for any $\kappa > 2$.

Theorem 6. *Assume κ is a positive number such that the condition (A_κ) is satisfied. Then, for any sufficiently large k, any ℓ and L satisfying*

$$2 + \kappa\frac{\log k}{\log 2} \le k - \ell \le L,$$

T_k does not have a gap of length at least L starting at ℓ.

Proof. Assume k is large enough, in particular $k > B_0$. It is well known (see, for instance, Theorem 320 in [2]), that

$$\sum_{n \le x} \tau(n) = x \log x + (2\gamma - 1)x + E(x),$$

where $|E(x)| < c_1\sqrt{x}$ for some positive constant c_1. For $x = 2^k$, we get

$$T_k = 2^k k \log 2 + 2^k(2\gamma - 1) + E(2^k). \tag{3}$$

Suppose now that T_k has a gap of length at least L starting at ℓ. Then the binary expansion of T_k is $T_k = \sum_{i=\ell+L}^{v_k} a_i 2^i + \sum_{i=0}^{\ell-1} a_i 2^i$, and, by (3), we get

$$\left|2^k k \log 2 + 2^{k+1}\gamma - b\right| < 2^\ell + E(2^k),$$

with $b = 2^k + \sum_{i=\ell+L}^{v_k} a_i 2^i$. Now, since $\ell + L \ge k$ and $2^k | b$, we can first divide by 2^k, and then apply Assumption (A_κ) with $b_0 = -2^{-k}b$, $b_1 = k$, $b_2 = 2$ to obtain

$$k^{-\kappa} \le |k \log 2 + 2\gamma + b_0| < 2^{\ell-k} + 2^{-k/2+2}. \tag{4}$$

Observe that in this case, in Assumption (A_κ) we have $B \le k$ since for k sufficiently large we have $b \le 2^k + T_k < k2^k$. We just have to observe that the inequality $2^{-k/2+2} < k^{-\kappa}/2$ holds for all sufficiently large k, to conclude that the last inequality (4) is impossible for any ℓ in the range $k \ge \ell + 2 + \kappa(\log k)/\log 2$. □

As a corollary of Theorem 6 and inequality (1), we give a criterion for the irrationality of the Euler's constant.

Corollary 7. *Assume that for infinitely many positive integers k, there exist ℓ and L satisfying*

$$2 + 3\left(\frac{\log k}{\log 2}\right) \le k - \ell \le L$$

and such that T_k has a gap of length at least L starting at ℓ. Then Euler's constant γ is irrational.

4. Further Comments

There are other similar games we can play in order to say something about the binary expansion of the average of other arithmetic functions evaluated in powers of 2 or in Fermat numbers, once the average value of such a function involves a constant for which we have a grasp on its irrationality measure. For example, using the fact (see for instance [2] §18.4, Th. 330) that

$$A(x) = \sum_{n \le x} \phi(n) = \frac{1}{2\zeta(2)} x^2 + O(x \log x)$$

together with the fact that the approximation exponent of $\zeta(2) = \pi^2/6$ is smaller than 5.5 (see [6]), then $s_2(A(2^n)) > (\log n)/\log(5.5) - c_2$, where c_2 is some positive constant. We give no further details.

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