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On Tribonacci numbers written as a product of three Fibonacci numbers

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Abstract

The present paper examines the following Diophantine equation: $T_n = F_k \cdot F_l \cdot F_m$ where T_n is the n-th Tribonacci number and likewise F_k is the k-th Fibonacci number and so on as variables. As an application of the Baker's method, we show that the equation has only one solution apart from the trivial one, namely $(n, k, l, m) = (12, 4, 6, 8)$. This paper can be considered as a continuation work of the paper by Luca et al, 2023.

1 Introduction

There are many recent papers in the literature addressing the Diophantine equation obtained by imposing that a member of some specific linearly recurrent sequence (Fibonacci numbers, Tribonacci numbers, powers of 2, etc.) equals a sum or product of two or three members of some other concrete linearly recurrent sequence [3], [9], [5]. The present paper does this for Tribonacci numbers which are products of three Fibonacci numbers. The method is classical: use Baker's method to iteratively bound indices as powers of logarithms of the largest one, ending up with a large upper bound on all the unknowns which afterwards needs to be lowered by using reduction methods such as the Baker-Davenport method.

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The motivation for this paper stems from the work in [5], and focusing on the equation:

$$T_n = F_k F_l F_m,$$

where T_n represents the n-th Tribonacci number, and F_k, F_l, F_m are Fibonacci numbers at indices k, l, and m, respectively. The problem seeks to determine the values of k, l, and m such that the product of these Fibonacci numbers equals a specific Tribonacci number.

We will show that this equation has only one positive solution.

Before stating the main results, let us start with some basic definitions and properties of the Fibonacci and Tribonacci numbers. Let $(F_n)_{n\geq 0}$ be the Fibonacci sequence given by $F_0 = 0, F_1 = 1$ and $F_{n+2} = F_{n+1} + F_n$ for $n \geq 0$ and its characteristic polynomial is $X^2 - X - 1 = (X - \psi)(X - \omega)$ where

$$\psi = \frac{1+\sqrt{5}}{2},$$

$$\omega = \frac{1-\sqrt{5}}{2}.$$

Let $(T_n)_{n\geq 0}$ be the Tribonacci sequence given by $T_0 = 0$, $T_1 = T_2 = 1$ and $T_{n+3} = T_{n+2} + T_{n+1} + T_n$ for $n \geq 0$.

The characteristic polynomial is $X^3 - X^2 - X - 1 = (X-\alpha)(X-\beta)(X-\gamma)$ where

$$\alpha = \frac{1 + \sqrt[3]{19+3\sqrt{33}} + \sqrt[3]{19-3\sqrt{33}}}{3},$$

$$\beta = \frac{1 + w\sqrt[3]{19+3\sqrt{33}} + w^2\sqrt[3]{19-3\sqrt{33}}}{3},$$

$$\gamma = \frac{1 + w^2\sqrt[3]{19+3\sqrt{33}} + w^3\sqrt[3]{19-3\sqrt{33}}}{3}.$$

In this paper, we investigate Diophantine equation

$$T_n = F_k F_l F_m \tag{1}$$

in positive unknowns n, k, l and m.

Theorem 1. *Apart from the trivial solutions, the unique positive integer solution quadruple* (n, k, l, m) *of Diophantine equation (1) is given by* $(12, 4, 6, 8)$.

In the next section, we recall a result due to Matveev concerning a lower bound for linear forms in logarithms of algebraic numbers, as well a variant of a reduction result due to Baker-Davenport reduction.

2 Properties of Fibonacci and Tribonacci sequences

It is well-known that the Binet formulas for Tribonacci sequence is

$$T_n = a\alpha^n + b\beta^n + c\gamma^n,$$

for n is nonnegative integers, where

$$a = \frac{5\alpha^2 - 3\alpha - 4}{22},$$

$$b = \frac{5\beta^2 - 3\beta - 4}{22},$$

$$c = \bar{b}, \gamma = \bar{\beta}$$

as in [5]. The minimal polynomial of a over integers is $44X^3 - 2X - 1$, with zeros a, b, c with $\max\{|a|, |b|, |c|\} \geq 1$. One can estimate following numerical values like in [5]:

$$1.83 \leq \alpha \leq 1.84;$$

$$0.73 \leq |\beta| = \alpha^{-1/2};$$

$$0.25 \leq |b| \leq 0.27.$$

For $n \geq 1$, denoting $e(n) := T_n - a\alpha^n$, one has

$$|e(n)| \leq \alpha^{\frac{-n}{2}} \tag{2}$$

as in [5]. Furthermore,

$$\alpha^{n-2} \leq T_n \leq \alpha^{n-1} \tag{3}$$

for all $n \geq 1$.

Binet formula for the Fibonacci sequence is $F_k = \frac{\psi^k - \omega^k}{\sqrt{5}}$ for all $k \geq 0$. Here we know that $\psi \cdot \omega = -1$. Furthermore, for $k \geq 1$, one has

$$\psi^{k-2} \leqslant F_k \leq \psi^{k-1} \tag{4}$$

for all $k \geq 1$.

3 Linear forms in logarithms

Let α be an algebraic number of degree d. Let $f(x) = \sum_{i=0}^{\infty} a_i x^{d-1} \in \mathbb{Z}[x]$ be the minimal polynomial of α with $a_0 \geq 1$ and $(a_0, \ldots, a_d) = 1$. Then, $H(\alpha) := max\{|a_i| : i = 0, \ldots, d\}$ and call it the height of α. And one can write $f(X) = a_0 \prod_{i=1}^{d}(X - \alpha^{(i)})$, where $\alpha = \alpha^{(i)}$. The logarithmic height of α is

$$h(\alpha) := \frac{1}{d}\Big(\log |a_0| + \sum_{i=1}^{d} \log \max\{|\alpha^{(i)}|, 1\}\Big)$$

The height has the following basic properties. For algebraic numbers α, β and $s \in \mathbb{Z}$, we have

$$h(\alpha \pm \beta) \leqslant h(\alpha) + h(\beta) + \log 2$$
$$h(\alpha\beta^{\pm 1}) \leqslant h(\alpha) + h(\beta)$$
$$h(\alpha^s) = |s|h(\alpha).$$

See reference [1] for more details.

Let L be a number field of degree D. Let $\alpha_1, \ldots, \alpha_n$ be non-zero elements of L and $b_1, \ldots, b_n$ be integers. Then,

$$B = \max\{|b_1|, \ldots, |b_n|\}$$

and

$$\Lambda = \prod_{i=1}^{n} \alpha_i^{b_i} - 1.$$

Let $A_1, \ldots, A_n$ be positive real numbers such that

$$A_j \geqslant h(\alpha_j) := \max\{Dh(\alpha_j), |\log \alpha_j|, 0.16\}$$

for all $j = 1, \ldots, n$.

With these notatitons, Matveev proved the following theorem [6].

Theorem 2. *If $\Lambda \neq 0$, then*

$$\log |\Lambda| > -1.4 \cdot 30^{n+3} \cdot n^{4.5} \cdot d_{\mathbb{K}}^2 \cdot (1 + \log d_{\mathbb{K}})(1 + \log B) \cdot A_1 \cdots A_n.$$

Lemma 3. *[8] If $l \geqslant 1$, $H > (4l^2)^l$ and $H > \frac{L}{(\log L)^l}$ then*

$$L < 2^l H(\log H)^l.$$

Lemma 4. *[7] For a positive real x, if $|x - 1| < 0.5$, then $|\log x| < 1.5|x - 1|$.*

The following result is a variation of a lemma by [2] and is attributed to [4].

Theorem 5. *Let M be a positive integer, let $\frac{p}{q}$ be a convergent of the continued fraction of the irrational number γ such that $q \geq 6M$ and let A, B, μ be some real numbers with $A \geq 0$ and $B \geq 1$. Let $\epsilon := ||\mu q|| - M||\gamma q||$. If $\epsilon \geq 0$, then there is no solution to the inequality*

$$0 \leq |m\gamma - n + \mu| \leq AB^{-m}$$

in positive integers m and n with

$$\frac{\log \frac{Aq}{\epsilon}}{\log B} \leq m \leq M.$$

4 The Proof of The Main Theorem

Let (n, k, l, m) be a solution of Diophantine equation (1). Because of $F_1 = F_2 = T_1 = T_2 = 1$, we suppose that $2 \leqslant k \leqslant l \leqslant m$ and $n \geqslant 2$. We assume that $k \geqslant 3$, because for $k = 2$, we get $T_n = F_l.F_m$ and this equation's proof is in [5]. From (3) and (4), we get

$$\alpha^{n-2} \leqslant T_n = F_k F_l F_m \leqslant \psi^{k+l+m-3}$$

and,

$$\psi^{k+l+m-6} \leqslant T_n = F_k F_l F_m \leqslant \alpha^{n-1}.$$

Thus,

$$(k+l+m)\frac{\log \psi}{\log \alpha} - 3.8 \leqslant n \leqslant (k+l+m)\frac{\log \psi}{\log \alpha} - 0.36. \tag{5}$$

Moreover, from equation (1) for $n \geqslant 4$ and $k \leqslant l \leqslant m$, we have

$$T_n = (\frac{\psi^k - \omega^k}{\sqrt{5}})(\frac{\psi^l - \omega^l}{\sqrt{5}})(\frac{\psi^m - \omega^m}{\sqrt{5}}),$$

$$\begin{aligned} T_n = \frac{1}{5\sqrt{5}}\Big(&\psi^{k+l+m} - \psi^{k+l}\omega^m - \psi^{k+m}\omega^l + \psi^k\omega^{l+m} \\ &- \psi^{l+m}\omega^k + \psi^l\omega^{k+m} + \psi^m\omega^{k+l} - \omega^{k+l+m}\Big). \end{aligned}$$

If $e(n) + a\alpha^n$ is substituted in place of T_n, and both sides are divided by $\frac{\psi^{k+l+m}}{5\sqrt{5}}$ and their absolute values are taken and from $\psi \cdot \omega = -1$, then the following inequality holds:

$$\left|\frac{5\sqrt{5}a\alpha^n}{\psi^{k+l+m}}-1\right| \le 5\sqrt{5}|e(n)|\psi^{-(k+l+m)}+|\psi|^{-2m}+|\psi|^{-2l}+|\psi|^{-2k} + |\psi|^{-2(l+m)}+|\psi|^{-2(k+m)}+|\psi|^{-2(k+l)} + |\psi|^{-2(k+l+m)}.$$

From (2) and the fact that $k \leqslant l \leqslant m$, we obtain that

$$\left|\frac{5\sqrt{5}\,a\,\alpha^n}{\psi^{k+l+m}}-1\right| \le 5\sqrt{5}\,\alpha^{-\frac{n}{2}}\,\psi^{-(k+l+m)}+3\psi^{-2k}+3\psi^{-4k}+\psi^{-6k} \le \psi^{-2k}\big(5\sqrt{5}\,\alpha^{-1}+7\big).$$

Thus, we obtain

$$\left|\frac{5\sqrt{5}a\alpha^n}{\psi^{k+l+m}}-1\right| \le 13.1\psi^{-2k}. \tag{6}$$

Now, let $\Lambda_1 := \frac{5\sqrt{5}a\alpha^n}{\psi^{k+l+m}}-1$. One can say $\Lambda_1 \neq 0$. Assuming $\Lambda_1 = 0$ gives $5\sqrt{5}a = \psi^{k+l+m}\alpha^{-n} \in \mathbb{K} := \mathbb{Q}(\alpha,\psi)$. Taking norms yields

$$N_{\mathbb{K}/\mathbb{Q}}(5\sqrt{5})N_{\mathbb{K}/\mathbb{Q}}(a) = \pm 1.$$

Since $|N_{\mathbb{K}/\mathbb{Q}}(5\sqrt{5})| = 5^9$ and $|N_{\mathbb{K}/\mathbb{Q}}(a)| = (1/44)^2$, we obtain $1 = 5^9/44^2$, a contradiction. Hence, $\Lambda_1 \neq 0$. So we have

$$|\Lambda_1| \le 13.1\psi^{-2k}. \tag{7}$$

We will use (Theorem 2) to get a lower bound for $|\Lambda_1|$. We set $t := 3$, $\eta_1 = \alpha$, $\eta_2 = \psi$, $\eta_3 = 5\sqrt{5}a$, $b_1 = n$, $b_2 = -(k+l+m)$ and $b_3 = 1$. We get

$$h(\eta_1) = h(\alpha) \le 0.204,$$

$$h(\eta_2) = h(\psi) \le 0.241,$$

$$h(\eta_3) = h(5\sqrt{5}a) \le h(5\sqrt{5}) + h(a) \le 3.676.$$

We have $d_{\mathbb{K}} = 6$ and can take $A_1 = 1.23$, $A_2 = 1.45$ and $A_3 = 22.06$. Finally we get $B = k+l+m$. So, (Theorem 2) says that

$$\log|\Lambda_1| \ge -1.132.10^{15}\log(k+l+m).$$

Comparing this with (6), we obtain

$$k\log\psi \le 5.66.10^{14}\log(k+l+m).$$

In the second step, we fix k and rewrite equation of (1) as

$$T_n = F_k(\frac{\psi^l - \omega^l}{\sqrt{5}})(\frac{\psi^m - \omega^m}{\sqrt{5}}),$$

$$a\alpha^n + e(n) = F_k(\frac{\psi^l - \omega^l}{\sqrt{5}})(\frac{\psi^m - \omega^m}{\sqrt{5}}),$$

$$\frac{a\alpha^n}{F_k} + \frac{e(n)}{F_k} = \frac{\psi^{l+m} - \psi^l\omega^m - \psi^m\omega^l - \omega^{l+m}}{5}.$$

Because from (2), $k \leqslant l \leqslant m$ and $\omega = \frac{-1}{\psi}$, we get

$$|\frac{5a\alpha^n}{F_k\psi^{l+m}} - 1| \leq \frac{5|e(n)|}{F_k\psi^{l+m}} + |\psi|^{-2m} + |\psi|^{-2l} + |\psi|^{-2(l+m)},$$

$$|\frac{5a\alpha^n}{F_k\psi^{l+m}} - 1| \leq \frac{5\alpha^{-1}}{F_k\psi^{l+m}} + 3\psi^{-2l}$$

and $l \leqslant m$ and $F_k \geqslant 2$, we obtain

$$|\frac{5a\alpha^n}{F_k\psi^{l+m}} - 1| \leq \frac{5\alpha^{-1}}{2\psi^{2l}} + 3\psi^{-2l} \leq 4.36\psi^{-2l}$$

Set

$$\Lambda_2 := \frac{5a\alpha^n}{F_k\psi^{l+m}} - 1. \tag{8}$$

Λ_2 is nonzero. Indeed, if $\Lambda_2 = 0$, then $5a/F_k$ would be a unit in $\mathbb{Q}(\alpha)$. Taking norms yields $(5^3/44)/F_k^3 = 1$, so $44F_k^3 = 5^3$, which has no integer solutions k. So, Λ_2 must also be non-zero. Thus, we get

$$|\Lambda_2| \leq 4.36 \cdot \psi^{-2l}. \tag{9}$$

Then $\eta_1 = \alpha$, $\eta_2 = \psi$, $\eta_3 = \frac{F_k}{5a}$, $b_1 = n$, $b_2 = -(l+m)$ and $b_3 = -1$. $B = l+m$.

$$h(\eta_1) \leq 0.204,$$

$$h(\eta_2) \leq 0.241,$$

$$h(\eta_3) = h(\frac{F_k}{5a}) \leq 2.871 + (k-1). \log\psi < 2.5k\log\psi.$$

$A_1 = 1.23,\ A_2 = 1.45,\ A_3 \geqslant 15k\log\psi.$

$$\log|\Lambda_2| > -7.7 \cdot 10^{14} k \log\psi \log(l+m). \tag{10}$$

From inequality (9) and (10) we obtain

$$l \log \psi < 3.85 \cdot 10^{14} k \log \psi \log (l+m) \tag{11}$$

and we know that $k \log \psi < 5.66 \cdot 10^{14} \log (k+l+m)$. Then we obtain that,

$$l \log \psi < 2.18 \cdot 10^{29} (\log (k+l+m))^2. \tag{12}$$

In this final step, we fix k and l and write again to equation (1)

$$a\alpha^n + e(n) = F_k F_l (\frac{\psi^m - \omega^m}{\sqrt{5}}),$$

and so we obtain

$$\frac{\sqrt{5} a \alpha^n}{F_k F_l} - \frac{\sqrt{5} a e(n)}{F_k F_l} = \psi^m - \omega^m,$$

$$\frac{\sqrt{5} a \alpha^n}{F_k F_l} - \psi^m = -\frac{\sqrt{5} a e(n)}{F_k F_l} - \omega^m.$$

Because from (2), $k \leqslant l \leqslant m$ and $\omega = \frac{-1}{\psi}$, we get

$$|\frac{\sqrt{5} a \alpha^n}{F_k F_l \psi^m} - 1| < 1.31 \cdot \frac{1}{\psi^m}. \tag{13}$$

In here we get

$$\Lambda_3 := \frac{\sqrt{5} a \alpha^n}{F_k F_l \psi^m} - 1.$$

Λ_3 is nonzero. Because, if $\Lambda_3 = 0$, then $5a^2/(F_k F_l)^2$ would be a unit in $\mathbb{Q}(\alpha)$, and taking norms we get $5^3/44^2 = (F_k F_l)^6$, which again has no integer solutions k, l. We get $\eta_1 = \alpha$, $\eta_2 = \psi$, $\eta_3 = \frac{F_k F_l}{\sqrt{5} a}$, $b_1 = n$, $b_2 = -m$ and $b_3 = -1$. So we have $B = m$. Since the polynomial $5a^2 X^2 - F_k F_l$ has η_3 as a root. Thus,

$$h(\eta_3) = h(\frac{F_k F_l}{\sqrt{5} a}) \leq \log F_k + \log F_l + \log \sqrt{5} + h(a) < 2.5 \cdot l \log \psi$$

Using (12), we get $A_3 = 15 \cdot l \log \psi$.

$$\log |\Lambda_3| > -8.393 \cdot 10^{43} (1 + \log m) \log^2 (k+l+m).$$

From (13) we know that $|\Lambda_3| < 1.31 \cdot \frac{1}{\psi^m}$, and from (12) we obtain

$$m \log \psi < 1.6786 \cdot 10^{44} \log m \log^2 (k+l+m). \tag{14}$$

Therefore we have

$$m < 3.492 \cdot 10^{44} \log m \log^2(k+l+m) < 3.492 \cdot 10^{44} \log^3(3m) \tag{15}$$

and so with help of Mathematica we obtain

$$m < 5.74 \cdot 10^{50}.$$

Then we can write

$$3m < 1.048 \cdot 10^{45} (\log(3m))^3 < 2^3 \cdot 1.048 \cdot 10^{45} (\log(1.048 \cdot 10^{45}))^3.$$

Applying Lemma 3 with $l = 3$, $L = 3m$ and $H = 1.048 \cdot 10^{45}$ finally with the help of Mathematica, we see that

$$m < 2.895 \cdot 10^{45}.$$

Next, we reduce the above bound by applying Theorem 5. We rewrite inequality (6) using Lemma 4 we have

$$0 < \left| \log \left(\frac{5\sqrt{5} a \alpha^n}{\psi^{(k+l+m)}} \right) \right| < 1.5 \cdot \left| \frac{5\sqrt{5} a \alpha^n}{\psi^{(k+l+m)}} - 1 \right| < 19.65 \cdot \psi^{-2k},$$

$$0 < |n \log \alpha + \log(5\sqrt{5}a) - (k+l+m) \log \psi| < 19.65 \cdot \psi^{-2k}.$$

And then we obtain that

$$0 < |n \frac{\log \alpha}{\log \psi} - (k+l+m) + \frac{\log(5\sqrt{5}a)}{\log \psi}| < 40.84 \cdot \psi^{-2k}. \tag{16}$$

Because of $\frac{\log \alpha}{\log \psi}$ is irrational, from (8) and (15) we have $m < 2.895 \cdot 10^{45}$. From (5) we get $n \leqslant (k+l+m) \frac{\log \psi}{\log \alpha} - 0.36$. Therefore we obtain $n \leqslant 6.86 \cdot 10^{45}$.

Applying Lemma 2 with $w = 2k$, $\tau = \frac{\log \alpha}{\log \psi}$, $\mu = \frac{\log(5\sqrt{5}a)}{\log \psi}$, $A = 40.84$, $B = \psi$, $M = 6.86 \cdot 10^{45}$. With the help of Mathematica, we find that the 93-st covergent of τ is

$$\frac{p_{93}}{q_{93}} = \frac{68103707654293876575970223487859617453819481978}{53779947418601993080261791426062259518964114253}.$$

Its denominator satisfies $q_{93} > 6M$ and $\epsilon := 0.39994 > 0$. Thus, inequality (16) has no solution for $k \geqslant 116.6$ Then, we say that

$$k \leqslant 116.$$

We get (11) for $k \leqslant 116$. Therefore $l < 4.466 \cdot 10^{16} \log(2m)$. We apply Lemma 3, $l = 1$, $H = 8.932 \cdot 10^{16}$, $L = 2l$ and we get $l < 4.71 \cdot 10^{18}$. And for $l < m$ and $m < 2.895 \cdot 10^{45}$ we write again (5)

$$n \leq (k + l + m)\frac{\log \psi}{\log \alpha} - 0.36$$

and we obtain

$$n < 2.287 \cdot 10^{45}.$$

We reduce the above bound by applying Theorem 5. We rewrite inequality (9) using Lemma 4, we have

$$0 < |n \log \alpha - (l + m) \log \psi + \log(\frac{5a}{F_k})| < 6.54 \cdot \psi^{-2l}.$$

$$0 < \left| n\frac{\log \alpha}{\log \psi} - (l + m) + \frac{\log(\frac{5a}{F_k})}{\log \psi} \right| < 13.6 \cdot \psi^{-2l}.$$

Applying Theorem 5 with $w = 2l$, $\tau = \frac{\log \alpha}{\log \psi}$, $\mu = (\log \frac{5a}{F_k})/(\log \psi)$, $A = 13.6$, $B = \psi$, $M = 2.287 \cdot 10^{45}$. With the help of Mathematica, we find that the 92-th covergent of τ is

$$\frac{p_{92}}{q_{92}} = \frac{20315058705469804724196191973044018196893122675}{16042339347101536940676670301036990567557791783}.$$

Its denominator satisfies $q_{92} > 6M$ and $\epsilon := 0.00215295 > 0$. Thus, inequality (16) has no solution for $l \geqslant 119.64$. And we say

$$l \leqslant 119.$$

Finally, we get (15) and obtain $m < 5.74 \cdot 10^{50}$. From (13) and Lemma 4 we have

$$0 < |\log(\frac{\sqrt{5}a\alpha^n}{F_k F_l \psi^m})| < 1.5 \cdot |\Lambda_3| < 1.5 \cdot 1.31 \cdot \psi^{-m}.$$

Then we obtain

$$0 < |n \log \alpha - m \log \psi + \log(\frac{\sqrt{5}a}{F_k F_l})| < 1.965 \cdot \psi^{-m},$$

and

$$0 < \left| n\frac{\log \alpha}{\log \psi} - m + \frac{\log(\frac{\sqrt{5}a}{F_k F_l})}{\log \psi} \right| < 4.09 \cdot \psi^{-m}.$$

In here we apply Theorem 5 with $w = m$, $\tau = \frac{\log \alpha}{\log \psi}$, $\mu = (\log \frac{\sqrt{5}a}{F_k F_l})/(\log \psi)$, $A = 4.09$, $B = \psi$, $M = 4.54 \cdot 10^{50}$. And with the help of Mathematica, we find that the 102-th covergent of τ is

$$\frac{p_{102}}{q_{102}} = \frac{357480320652447077123391739476879443922379891984550 48}{2822940704706471005673233534655821128210784947408 6397}.$$

Its denominator satisfies $q_{102} > 6M$ and $\epsilon > 0.0000535443 > 0$. Thus, inequality (16) has no solution for $m \geqslant 274.34$. And we say

$$m \leqslant 274.$$

Hence $k \leqslant 116, l \leqslant 119, m \leqslant 274$. Using Mathematica, we determined bounds for k, l and m and found that the only solution is

$$(n, k, l, m) \in (12, 4, 6, 8).$$

And this finishes the proof.

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