

PROOF OF THE CONTINUED FRACTION CONJECTURE FOR

$$(a, b) = (z^3, z^3 + 1)$$

GUO-NIU HAN* AND YINING HU*

ABSTRACT. The continued fraction conjecture claims that the continued fraction defined by the (a, b) -Thue-Morse sequence is algebraic over $\mathbb{F}_2(x)$ for all pairs of distinct elements (a, b) in $\mathbb{F}_2[x] \setminus \mathbb{F}_2$. In this paper we prove the conjecture for $(a, b) = (z^3, z^3 + 1)$.

1. INTRODUCTION

Let $\mathbb{F}_2$ be the finite field of cardinality 2. Given a sequence of polynomials $\mathbf{a} = (a_0(z), a_1(z), a_2(z), \dots)$ of elements from $\mathbb{F}_2[z] \setminus \mathbb{F}_2$, we define the infinite continued fraction

$$(1.1) \quad \text{CF}(\mathbf{a}(z)) = \frac{1}{a_0(z) + \frac{1}{a_1(z) + \frac{1}{a_2(z) + \frac{1}{\ddots}}}}$$

as the limit of the finite continued fractions

$$(1.2) \quad \text{CF}_n(\mathbf{a}(z)) = \frac{1}{a_0(z) + \frac{1}{a_1(z) + \frac{1}{\ddots + \frac{1}{a_n(z)}}}} \in \mathbb{F}_2((1/z)).$$

Conversely, each power series in $\mathbb{F}_2[[1/z]]$ without constant term

$$(1.3) \quad c_{-1}z^{-1} + c_{-2}z^{-2} + c_{-3}z^{-3} + \dots$$

admits a continued fraction expansion of form (1.1).

Let a and b be two distinct elements from $\mathbb{F}_2[z] \setminus \mathbb{F}_2$. We consider the continued fraction (1.1) associated with the (a, b) -Thue-Morse sequence

$$\mathbf{t} = (t_0(z), t_1(z), t_2(z), \dots) = (a, b, b, a, b, a, a, b, \dots)$$

that we shall denote

$$(1.4) \quad \text{CF}(a, b) := \text{CF}(\mathbf{t}).$$

Date: 9/04/2020 09:28:13 .

2010 Mathematics Subject Classification. 11B85, 11J70, 11B50, 11Y65, 05A15.

Key words and phrases. automatic sequence, continued fraction, Thue-Morse sequence.

* This paper was automatically generated from a computer program developed by the authors, with 8.0 minutes CPU time used.

Theorem 1.1. *When $(a, b) = (z^3, z^3 + 1)$, the two power series $\text{CF}(a, b)$ and $\text{CF}(b, a)$ are algebraic over $\mathbb{F}_2(z)$, with minimal polynomials of the form*

$$p_4(z)y^4 + p_3(z)y^3 + p_2(z)y^2 + p_1(z)y + p_0(z) = 0$$

where, for $\text{CF}(a, b)$,

$$\begin{aligned} p_0(z) &= z^{18} + z^{15} + z^{12} + z^9 + z^3 + 1, \\ p_1(z) &= z^{18} + z^{15} + z^{12} + z^9 + z^6 + z^3, \\ p_2(z) &= z^{24} + z^6, \\ p_3(z) &= z^{18} + z^{15} + z^{12} + z^9 + z^6 + z^3, \\ p_4(z) &= z^{18} + z^{15} + z^9 + z^6 + z^3, \end{aligned}$$

and for $\text{CF}(b, a)$,

$$\begin{aligned} p_0(z) &= z^{18} + z^{15} + z^{12} + z^9 + z^3, \\ p_1(z) &= z^{18} + z^{15} + z^{12} + z^9 + z^6 + z^3, \\ p_2(z) &= z^{24} + z^6, \\ p_3(z) &= z^{18} + z^{15} + z^{12} + z^9 + z^6 + z^3, \\ p_4(z) &= z^{18} + z^{15} + z^9 + z^6 + z^3 + 1. \end{aligned}$$

2. PROOF

Define the sequences of polynomials $(P_n(z))_{n \geq 0}$ and $(Q_n(z))_{n \geq 0}$ by

$$\begin{pmatrix} P_n(z) & Q_n(z) \\ P_{n-1}(z) & Q_{n-1}(z) \end{pmatrix} := \begin{pmatrix} t_n(z) & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} t_{n-1}(z) & 1 \\ 1 & 0 \end{pmatrix} \cdots \begin{pmatrix} t_0(z) & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}.$$

By the basic properties of continued fractions, we have

$$(2.1) \quad \text{CF}_n(a, b) = \frac{P_n(z)}{Q_n(z)} \in \mathbb{F}_2((1/z)).$$

As formula (2.1) is not efficient for calculating $\text{CF}_n(a, b)$, a fast method is to be derived and described as follows. Define

$$\begin{aligned} M_n(x) &= x^{\deg(t_{2^n-1})} \begin{pmatrix} t_{2^n-1}(1/x) & 1 \\ 1 & 0 \end{pmatrix} \times x^{\deg(t_{2^n-2})} \begin{pmatrix} t_{2^n-2}(1/x) & 1 \\ 1 & 0 \end{pmatrix} \times \\ &\quad \cdots \times x^{\deg(t_0)} \begin{pmatrix} t_0(1/x) & 1 \\ 1 & 0 \end{pmatrix}, \\ W_n(x) &= x^{\deg(\bar{t}_{2^n-1})} \begin{pmatrix} \bar{t}_{2^n-1}(1/x) & 1 \\ 1 & 0 \end{pmatrix} \times x^{\deg(\bar{t}_{2^n-2})} \begin{pmatrix} \bar{t}_{2^n-2}(1/x) & 1 \\ 1 & 0 \end{pmatrix} \times \\ &\quad \cdots \times x^{\deg(\bar{t}_0)} \begin{pmatrix} \bar{t}_0(1/x) & 1 \\ 1 & 0 \end{pmatrix}, \end{aligned}$$

where $\bar{t}$ is the (b, a) -Thue-Morse sequence. By the properties of the Thue-Morse sequence, we have for $n \geq 0$

$$\begin{aligned} M_{n+1}(x) &= W_n(x) \cdot M_n(x), \\ W_{n+1}(x) &= M_n(x) \cdot W_n(x). \end{aligned}$$

Let $x := 1/z$. For each non-zero polynomial $P(z)$, define $\tilde{P}(x)$ to be $P(1/x)$. Then,

$$\text{CF}_n(a, b) = \frac{P_n(z)}{Q_n(z)} = \frac{\tilde{P}_n(x)}{\tilde{Q}_n(x)} \in \mathbb{F}_2((x)) = \mathbb{F}_2((1/z)).$$

Comparing the definition of $M_n(x)$ with the definition of $P_n(x)$ and $Q_n(x)$, we see that

$$\begin{aligned} M_n(x)_{0,1} &= x^{d_n} \tilde{P}_{2^n-1}(x), \\ M_n(x)_{0,0} &= x^{d_n} \tilde{Q}_{2^n-1}(x), \end{aligned}$$

for some positive integer d_n . Hence,

$$(2.2) \quad \text{CF}_{2^{2^n}-1}(a, b) = \frac{\tilde{P}_{2^{2^n}-1}(x)}{\tilde{Q}_{2^{2^n}-1}(x)} = \frac{M_{2^n}(x)_{0,1}}{M_{2^n}(x)_{0,0}}.$$

Therefore, by the convergence theorem of continued fraction, the algebraicity of $\text{CF}(a, b)$ will be established if it is shown that both $M_{2^n}(x)_{0,1}$ and $M_{2^n}(x)_{0,0}$ converge to algebraic series in $\mathbb{F}_2[[x]]$.

Actually, we will prove that for all $0 \leq i, j \leq 1$ the four sequences $(M_{2^n}(x)_{i,j})_n$, $(M_{2^{n+1}}(x)_{i,j})_n$, $(W_{2^n}(x)_{i,j})_n$, and $(W_{2^{n+1}}(x)_{i,j})_n$ converge to algebraic series in $\mathbb{F}_2[[x]]$. For this purpose, we define four 2×2 matrices M^e, M^o, W^e, W^o as follows: For each $T \in \{M^e, M^o, W^e, W^o\}$ and $0 \leq i, j \leq 1$, $T_{i,j}$ is defined to be the unique solution in $\mathbb{F}_2[[x]]$ of the polynomial $\phi(T, i, j)$ under certain initial conditions; the polynomials $\phi(T, i, j)$ and initial conditions are given in Section 3. We will prove that these four matrices, whose components are algebraic by definition, are the limits of $(M_{2^n}(x))_n$, $(M_{2^{n+1}}(x))_n$, $(W_{2^n}(x))_n$, and $(W_{2^{n+1}}(x))_n$.

Let us explain how the polynomials $\phi(T, i, j)$ and initial conditions are found, and why the solutions exist and are unique. For $0 \leq i, j \leq 1$, the coefficients of the polynomial $\phi(M^e, i, j)$ (resp. $\phi(M^o, i, j)$, $\phi(W^e, i, j)$, and $\phi(W^o, i, j)$) are the Padé-Hermite approximants of type

$$(150, 150, 150, 150, 150)$$

of the vector

$$(1, T^3, T^6, T^9, T^{12}),$$

where $T = M_{12,i,j}$ (resp. $M_{11,i,j}$, $W_{12,i,j}$, and $W_{11,i,j}$), found by the Derksen algorithm. We take the first 8 terms of $M_{12,i,j}$ (resp. $M_{11,i,j}$, $W_{12,i,j}$, and $W_{11,i,j}$) as initial conditions for $\phi(M^e, i, j)$ (resp. $\phi(M^o, i, j)$, $\phi(W^e, i, j)$, and $\phi(W^o, i, j)$). The following fact will be used to ensure that the solution exists and is unique: let $P(x, y) \in \mathbb{F}_2[x, y]$ and for each series $f(x) = \sum_{n=0}^{\infty} a_n x^n \in \mathbb{F}_2[[x]]$ denote the partial sum $\sum_{j=0}^{n-1} a_j x^j$ by $f_n(x)$ for $n \geq 0$. If for some $n \geq 0$ and $a_0, a_1, \dots, a_{n-1} \in \mathbb{F}_2$ $P(x, \sum_{j=0}^{n-1} a_j x^j) = O(x^n)$ and $Q(x, y) := P(x, \sum_{j=0}^{n-1} a_j x^j + x^n y)$ can be written as $x^m \sum_{j=0}^{\infty} q_j(x) y^j$ where $q_j(x)$ are polynomials for $j \geq 0$, $q_1(0) = 1$, and $q_j(0) = 0$ for $j > 1$, then there exists a unique solution $f(x) \in \mathbb{F}_2[[x]]$ of $P(x, f(x)) = 0$ that satisfies the initial condition $f_n(x) = \sum_{j=0}^{n-1} a_j x^j$.

We state two lemmas concerning the four matrices M^e, M^o, W^e, W^o . The first one is about relations between them; the second, about the structure of the each matrix.

Lemma 2.1. *We have*

$$(2.3) \quad M^e = W^o \cdot M^o,$$

$$(2.4) \quad M^o = W^e \cdot M^e,$$

$$(2.5) \quad W^e = M^o \cdot W^o,$$

$$(2.6) \quad W^o = M^e \cdot W^e.$$

Proof. We give the proof of the identity

$$M_{0,0}^e = W_{0,0}^o M_{0,0}^o + W_{0,1}^o M_{1,0}^o,$$

the proofs of the others being similar.

First, we compute the minimal polynomials of $W_{0,0}^o M_{0,0}^o$ and $W_{0,1}^o M_{1,0}^o$. We know that

$$P(x, y) = \text{Res}_z (\phi(W^o, 0, 0)(x, z), z^{12} \cdot \phi(M^o, 0, 0)(x, y/z))$$

is an annihilating polynomial of $W_{0,0}^o M_{0,0}^o$. We use Padé-Hermite approximation to find a candidate for the minimal polynomial of $W_{0,0}^o M_{0,0}^o$, that will be called $\phi_0(x, y)$. To prove that $\phi_0(x, y)$ is indeed the minimal polynomial, it suffices to prove that it is an irreducible factor of $P(x, y)$ of multiplicity m and that $Q(x, y) := P(x, y)/\phi_0(x, y)^m$ is not an annihilating polynomial of $W_{0,0}^o M_{0,0}^o$. We verify the first point directly. For the second point, we truncate $W_{0,0}^o M_{0,0}^o$ to order 540 and substitute it for y in $Q(x, y)$. We get a series of valuation less than 540, which proves that $Q(x, y)$ is not an annihilating polynomial of $W_{0,0}^o M_{0,0}^o$. We find the minimal polynomial $\phi_1(x, y)$ of $W_{0,1}^o M_{1,0}^o$ in a similar way.

Now we prove that $\phi(M^e, 0, 0)$ is the minimal polynomial of $W_{0,0}^o M_{0,0}^o + W_{0,1}^o M_{1,0}^o$. We know that

$$S(x, y) = \text{Res}_z (\phi_0(x, z), \phi_1(x, y + z))$$

is an annihilating of $W_{0,0}^o M_{0,0}^o + W_{0,1}^o M_{1,0}^o$. We verify that $\phi(M^e, 0, 0)$ is an irreducible factor of $S(x, y)$ of multiplicity μ , and that $Q(x, y) := S(x, y)/\phi(M^e, 0, 0)^\mu$ is not an annihilating polynomial of $W_{0,0}^o M_{0,0}^o + W_{0,1}^o M_{1,0}^o$. To see the last point, we truncate $W_{0,0}^o M_{0,0}^o + W_{0,1}^o M_{1,0}^o$ to order 660 and substitute it for y in $Q(x, y)$. We get a series of valuation less than 660, and therefore $Q(x, y)$ is not an annihilating polynomial of $W_{0,0}^o M_{0,0}^o + W_{0,1}^o M_{1,0}^o$.

Finally, the first 32 terms of $M_{0,0}^e$ and $W_{0,0}^o M_{0,0}^o + W_{0,1}^o M_{1,0}^o$ coincide. As these first terms determine a unique solution of $\phi(M^e, 0, 0)$, we know that the two series are one and the same. $\square$

Define

$$R^e = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad \text{and} \quad R^o = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}.$$

Lemma 2.2. *For all integers $k \geq 2$ and $u = 2^{2k-1}$, the following identities hold.*

$$\begin{aligned} M^e[:12u] &= M^e[:6u] + x^{3u} M^e[:3u] + x^{3u} M^e[:6u] + x^{6u} M^e[:3u] + x^{6u} M^e[:6u] \\ &\quad + (x^{6u} + x^{9u}) R^e, \\ W^e[:12u] &= W^e[:6u] + x^{3u} W^e[:3u] + x^{3u} W^e[:6u] + x^{6u} W^e[:3u] + x^{6u} W^e[:6u] \\ &\quad + (x^{6u} + x^{9u}) R^e. \end{aligned}$$

For all integers $k \geq 2$ and $u = 2^{2k}$, the following identities hold.

$$M^o[:12u] = M^o[:6u] + x^{3u} M^o[:3u] + x^{3u} M^o[:6u] + x^{6u} M^o[:3u] + x^{6u} M^o[:6u]$$

$$\begin{aligned}
& + (x^{6u} + x^{9u})R^o, \\
W^o[:12u] &= W^o[:6u] + x^{3u}W^o[:3u] + x^{3u}W^o[:6u] + x^{6u}W^o[:3u] + x^{6u}W^o[:6u] \\
& + (x^{6u} + x^{9u})R^o.
\end{aligned}$$

Proof. To prove Lemma 2.2 we first construct an automaton for each sequence concerned, and then transform the conditions on infinitely many k 's into finitely many conditions on the states of the automaton. In the following, we will prove that for $T = M_{0,0}^o$, for all integer $k \geq 2$ and $u = 2^{2k}$,

$$T[:12u] = T[:6u] + x^{3u}T[:3u] + x^{3u}T[:6u] + x^{6u}T[:3u] + x^{6u}T[:6u].$$

The proof of the other 15 cases are similar. We break down the above identity into 6 parts:

$$\begin{aligned}
0 &= x^{3u}T[3u:4u] + T[6u:7u], \\
0 &= x^{3u}T[4u:5u] + T[7u:8u], \\
0 &= x^{3u}T[5u:6u] + T[8u:9u], \\
0 &= x^{6u}T[3u:4u] + T[9u:10u], \\
0 &= x^{6u}T[4u:5u] + T[10u:11u], \\
0 &= x^{6u}T[5u:6u] + T[11u:12u],
\end{aligned}$$

which can be rewritten as

$$\begin{aligned}
(2.7) \quad 0 &= T[[11w]_2] + T[[110w]_2], \\
(2.8) \quad 0 &= T[[100w]_2] + T[[111w]_2], \\
(2.9) \quad 0 &= T[[101w]_2] + T[[1000w]_2], \\
(2.10) \quad 0 &= T[[11w]_2] + T[[1001w]_2], \\
(2.11) \quad 0 &= T[[100w]_2] + T[[1010w]_2], \\
(2.12) \quad 0 &= T[[101w]_2] + T[[1011w]_2],
\end{aligned}$$

for all binary word w of length $2k$ and $w \neq 0^{2k}$, and

$$\begin{aligned}
(2.13) \quad 0 &= T[[11w]_2] + T[[110w]_2], \\
(2.14) \quad 0 &= T[[100w]_2] + T[[111w]_2], \\
(2.15) \quad 0 &= T[[101w]_2] + T[[1000w]_2], \\
(2.16) \quad 0 &= T[[11w]_2] + T[[1001w]_2], \\
(2.17) \quad 0 &= T[[100w]_2] + T[[1010w]_2], \\
(2.18) \quad 0 &= T[[101w]_2] + T[[1011w]_2],
\end{aligned}$$

for $w = 0^{2k}$.

First we calculate an 2-automaton that generates T from its minimal polynomial and its first terms. This automaton has 60 states; its transition function and output function can be found in the annex. Let $A(s, w)$ denote the state reached after reading w from right to left starting from the state s , and τ the output function. Define

$$E_{2k} = \{A(i, w) : |w| = 2k, w \neq 0^{2k}\}.$$

Identities (2.7) through (2.18) can be written as

$$\begin{aligned}
(2.19) \quad & 0 = \tau(A(s, 11)) + \tau(A(s, 110)), \\
(2.20) \quad & 0 = \tau(A(s, 100)) + \tau(A(s, 111)), \\
(2.21) \quad & 0 = \tau(A(s, 101)) + \tau(A(s, 1000)), \\
(2.22) \quad & 0 = \tau(A(s, 11)) + \tau(A(s, 1001)), \\
(2.23) \quad & 0 = \tau(A(s, 100)) + \tau(A(s, 1010)), \\
(2.24) \quad & 0 = \tau(A(s, 101)) + \tau(A(s, 1011)),
\end{aligned}$$

for all $s \in E_{2k}$, and

$$\begin{aligned}
(2.25) \quad & 0 = \tau(A(s, 11)) + \tau(A(s, 110)), \\
(2.26) \quad & 0 = \tau(A(s, 100)) + \tau(A(s, 111)), \\
(2.27) \quad & 0 = \tau(A(s, 101)) + \tau(A(s, 1000)), \\
(2.28) \quad & 0 = \tau(A(s, 11)) + \tau(A(s, 1001)), \\
(2.29) \quad & 0 = \tau(A(s, 100)) + \tau(A(s, 1010)), \\
(2.30) \quad & 0 = \tau(A(s, 101)) + \tau(A(s, 1011)),
\end{aligned}$$

for $s = A(i, 0^{2k})$. We find that $(A(i, 0^{12}), E_{12}) = (A(i, 0^{10}), E_{10})$, so that we only have to verify that identities (2.19) through (2.30) hold for $2 \leq k \leq 6$, which turns out to be true. $\square$

In the following lemma, we express M_{2k} , M_{2k+1} , W_{2k} , and W_{2k+1} in terms of M^e , M^o , W^e , and W^o .

Lemma 2.3. *For all integer $k \geq 2$, and $u = 2^{2k-1}$,*

$$\begin{aligned}
M_{2k} &= M^e[:6u] + x^{3u}M^e[:3u] + x^{6u}R^e, \\
W_{2k} &= W^e[:6u] + x^{3u}W^e[:3u] + x^{6u}R^e.
\end{aligned}$$

For all integer $k \geq 2$, and $u = 2^{2k}$,

$$\begin{aligned}
M_{2k+1} &= M^o[:6u] + x^{3u}M^o[:3u] + x^{6u}R^o, \\
W_{2k+1} &= W^o[:6u] + x^{3u}W^o[:3u] + x^{6u}R^o.
\end{aligned}$$

Proof. We call the four identities in Lemma 2.3 also by the name M_{2k} , W_{2k} , M_{2k+1} , and W_{2k+1} . For $n = 2$, the identities can be verified directly. For $n \geq 2$, we claim that

$$\begin{aligned}
M_{2k} \wedge W_{2k} &\Rightarrow M_{2k+1} \wedge W_{2k+1}, \\
M_{2k+1} \wedge W_{2k+1} &\Rightarrow M_{2k+2} \wedge W_{2k+2}.
\end{aligned}$$

We give the proof of

$$M_{2k} \wedge W_{2k} \Rightarrow M_{2k+1},$$

the other ones being similar. Set $u = 2^{2k}$ and $v = 2^{2k-1}$. By definition and induction hypothesis, the left side of identity M_{2k+1} is equal to

$$\begin{aligned}
(2.31) \quad & W_{2k}M_{2k} = (W^e[:6v] + x^{3v}W^e[:3v] + x^{6v}R^e) \times (M^e[:6v] + x^{3v}M^e[:3v] \\
& + x^{6v}R^e);
\end{aligned}$$

Call this expression *lhs*. Note that both sides of identity M_{2k+1} have the same term of highest degree $x^{12v}R^o$. Therefore we only need to prove that their difference is

$O(x^{12v})$. Using Lemma 2.1 it can be seen that the right side of identity M_{2k+1} is congruent, modulo x^{12v} , to

$$W^e[:12v]M^e[:12v] + x^{6v}W^e[:6v]M^e[:6v].$$

For all $n \leq 12$, replace the occurrences of $W^e[:n \cdot v]$ and $M^e[:n \cdot v]$ in the above expression by the reduction modulo $x^{n \cdot v}$ of the right side of the corresponding identity in Lemma 2.2 and get a new expression, which we call *rhs*. Define

$$\begin{aligned} X &:= x^v, \\ a_n &:= W^e[n \cdot v : (n+1) \cdot v] / X^n, \\ b_n &:= M^e[n \cdot v : (n+1) \cdot v] / X^n, \\ c &:= R^e. \end{aligned}$$

Using the notation introduced above, we can represent the expressions *lhs* (2.31) and *rhs* as polynomials in $\mathbb{F}_2[a_1, \dots, a_{12}, b_1, \dots, b_{12}, c][X]$. Note that it is not a problem that a_j commutes with b_k while W^e does not commute with M^e , because in the expressions concerned, the products of W^e -terms and M^e -terms are always in the same order. We let the computer do the simplification and check that the difference between these two polynomials is indeed $O(X^{12})$, which completes the proof. $\square$

Proof of Theorem 1.1. We prove the theorem for $\text{CF}(a, b)$; for $\text{CF}(b, a)$, the proof is similar. By Lemma 2.3, we have For all $0 \leq j, k \leq 1$,

$$\begin{aligned} \lim_{n \rightarrow \infty} M_{2n, j, k} &= M_{j, k}^e, \\ \lim_{n \rightarrow \infty} M_{2n+1, j, k} &= M_{j, k}^o, \\ \lim_{n \rightarrow \infty} W_{2n, j, k} &= W_{j, k}^e, \\ \lim_{n \rightarrow \infty} W_{2n+1, j, k} &= W_{j, k}^o. \end{aligned}$$

Let $z = 1/x$. By the convergence theorem and identity (2.2),

$$\text{CF}(a, b) = \frac{M_{0,1}^e(x)}{M_{0,0}^e(x)}.$$

By definition, $\phi(M^e, 0, 1)$ and $\phi(M^e, 0, 0)$ are minimal polynomials of $M_{0,1}^e$ and $M_{0,0}^e$. Therefore

$$P(x, y) = \text{Res}_t (\phi(M^e, 0, 1)(x, t), y^{12}\phi(M^e, 0, 1)(x, t/y))$$

is an annihilating polynomial of $f(x) = M_{0,1}^e/M_{0,0}^e$.

Define

$$Q(x, y) = q_4(x)y^4 + q_3(x)y^3 + q_2(x)y^2 + q_1(x)y + q_0(x),$$

where

$$\begin{aligned} q_0(x) &= x^{24} + x^{21} + x^{15} + x^{12} + x^9 + x^6, \\ q_1(x) &= x^{21} + x^{18} + x^{15} + x^{12} + x^9 + x^6, \\ q_2(x) &= x^{18} + 1, \\ q_3(x) &= x^{21} + x^{18} + x^{15} + x^{12} + x^9 + x^6, \\ q_4(x) &= x^{21} + x^{18} + x^{15} + x^9 + x^6. \end{aligned}$$

The polynomial $Q(x, y)$ is the candidate for the minimal polynomial of $f(x)$ found by Padé-Hermite approximation. To prove that it is indeed the minimal polynomial of $f(x)$, we only need to prove that it is an irreducible factor of $P(x, y)$ of multiplicity m and $R(x, y) := P(x, y)/Q(x, y)^m$ is not an annihilating polynomial of $f(x)$. We verify the first point directly. For the second point, we find that when we truncate $f(x)$ to order 186, and substitute it for y in $R(z, y)$, we get a series with valuation smaller than 186, which proves that $R(z, y)$ is not an annihilating polynomial of $f(x)$. Finally, $z^{12}Q(1/z, y)$ is the minimal polynomial of $\text{CF}(a, b) = f(1/z)$. $\square$

3. ANNEXE

All 16 polynomials are of the form

$$p_0(x) + p_3(x)y^3 + p_6(x)y^6 + p_9(x)y^9 + p_{12}(x)y^{12}.$$

The coefficients $p_j(x)$ and the 32 initial terms to determine the solutions uniquely are given below.

For $\phi(M^e, 0, 0)$:

$$\begin{aligned} p_0(x) &= x^{126} + x^{120} + x^{108} + x^{102} + x^{84} + x^{60} + x^{48} + x^{42} + x^{36}, \\ p_3(x) &= x^{114} + x^{102} + x^{90} + x^{84} + x^{78} + x^{72} + x^{66} + x^{60} + x^{54} + x^{48} + x^{36} \\ &\quad + x^{24}, \\ p_6(x) &= x^{108} + x^{102} + x^{90} + x^{84} + x^{78} + x^{66} + x^{60} + x^{54} + x^{48} + x^{42} + x^{24} + 1 \\ &\quad , \\ p_9(x) &= x^{120} + x^{114} + x^{102} + x^{90} + x^{84} + x^{48} + x^{42} + x^{30} + x^{18} + x^{12}, \\ p_{12}(x) &= x^{120} + x^{96} + x^{72} + x^{48} + x^{24} + 1, \end{aligned}$$

and the initial terms are $[1, 0, 0, 0, 0, 0, 1, 0]$.

For $\phi(M^e, 0, 1)$:

$$\begin{aligned} p_0(x) &= x^{126} + x^{123} + x^{111} + x^{108} + x^{105} + x^{102} + x^{99} + x^{93} + x^{90} + x^{87} \\ &\quad + x^{84} + x^{81} + x^{78} + x^{69} + x^{60} + x^{48} + x^{45} + x^{39} + x^{36}, \\ p_3(x) &= x^{120} + x^{102} + x^{96} + x^{78} + x^{72} + x^{54}, \\ p_6(x) &= x^{117} + x^{114} + x^{111} + x^{108} + x^{105} + x^{102} + x^{99} + x^{96} + x^{81} + x^{78} \\ &\quad + x^{75} + x^{72} + x^{57} + x^{54} + x^{51} + x^{48} + x^{45} + x^{42} + x^{39} + x^{36}, \\ p_9(x) &= x^{114} + x^{108} + x^{102} + x^{90} + x^{84} + x^{72} + x^{60} + x^{48} + x^{42} + x^{30} + x^{24} \\ &\quad + x^{18}, \\ p_{12}(x) &= x^{111} + x^{108} + x^{99} + x^{96} + x^{63} + x^{60} + x^{51} + x^{48} + x^{15} + x^{12} + x^3 + 1, \end{aligned}$$

and the initial terms are $[0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]$.

For $\phi(M^e, 1, 0)$:

$$\begin{aligned} p_0(x) &= x^{126} + x^{123} + x^{111} + x^{108} + x^{105} + x^{102} + x^{99} + x^{93} + x^{90} + x^{87} \\ &\quad + x^{84} + x^{81} + x^{78} + x^{69} + x^{60} + x^{48} + x^{45} + x^{39} + x^{36}, \\ p_3(x) &= x^{120} + x^{102} + x^{96} + x^{78} + x^{72} + x^{54}, \end{aligned}$$

$$p_6(x) = x^{117} + x^{114} + x^{111} + x^{108} + x^{105} + x^{102} + x^{99} + x^{96} + x^{81} + x^{78} \\ + x^{75} + x^{72} + x^{57} + x^{54} + x^{51} + x^{48} + x^{45} + x^{42} + x^{39} + x^{36},$$

$$p_9(x) = x^{114} + x^{108} + x^{102} + x^{90} + x^{84} + x^{72} + x^{60} + x^{48} + x^{42} + x^{30} + x^{24} \\ + x^{18},$$

$$p_{12}(x) = x^{111} + x^{108} + x^{99} + x^{96} + x^{63} + x^{60} + x^{51} + x^{48} + x^{15} + x^{12} + x^3 + 1,$$

and the initial terms are $[0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0]$.

For $\phi(M^e, 1, 1)$:

$$p_0(x) = x^{126} + x^{108} + x^{96} + x^{90} + x^{72} + x^{66} + x^{60} + x^{48} + x^{36},$$

$$p_3(x) = x^{108} + x^{90} + x^{84} + x^{78} + x^{72} + x^{66} + x^{60} + x^{54} + x^{48} + x^{42} + x^{30} \\ + x^{24},$$

$$p_6(x) = x^{108} + x^{102} + x^{84} + x^{78} + x^{60} + x^{48} + x^{30} + x^{24} + x^6 + 1,$$

$$p_9(x) = x^{102} + x^{90} + x^{84} + x^{72} + x^{66} + x^{48} + x^{42} + x^{30} + x^{24} + x^{12},$$

$$p_{12}(x) = x^{102} + x^{96} + x^{54} + x^{48} + x^6 + 1,$$

and the initial terms are $[0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0]$.

For $\phi(W^e, 0, 0)$:

$$p_0(x) = x^{126} + x^{114} + x^{102} + x^{96} + x^{90} + x^{72} + x^{66} + x^{54} + x^{36},$$

$$p_3(x) = x^{108} + x^{96} + x^{90} + x^{78} + x^{66} + x^{54} + x^{42} + x^{36} + x^{30} + x^{24},$$

$$p_6(x) = x^{108} + x^{102} + x^{96} + x^{90} + x^{84} + x^{66} + x^{60} + x^{54} + x^{48} + x^{42} + x^6 + 1,$$

$$p_9(x) = x^{102} + x^{90} + x^{84} + x^{72} + x^{66} + x^{48} + x^{42} + x^{30} + x^{24} + x^{12},$$

$$p_{12}(x) = x^{102} + x^{96} + x^{54} + x^{48} + x^6 + 1,$$

and the initial terms are $[1, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0]$.

For $\phi(W^e, 0, 1)$:

$$p_0(x) = x^{126} + x^{117} + x^{111} + x^{102} + x^{93} + x^{87} + x^{84} + x^{81} + x^{78} + x^{75} + x^{72} \\ + x^{66} + x^{63} + x^{48} + x^{45} + x^{39} + x^{36},$$

$$p_3(x) = x^{120} + x^{102} + x^{96} + x^{78} + x^{72} + x^{54},$$

$$p_6(x) = x^{117} + x^{114} + x^{111} + x^{108} + x^{105} + x^{102} + x^{99} + x^{96} + x^{81} + x^{78} \\ + x^{75} + x^{72} + x^{57} + x^{54} + x^{51} + x^{48} + x^{45} + x^{42} + x^{39} + x^{36},$$

$$p_9(x) = x^{114} + x^{108} + x^{102} + x^{90} + x^{84} + x^{72} + x^{60} + x^{48} + x^{42} + x^{30} + x^{24} \\ + x^{18},$$

$$p_{12}(x) = x^{111} + x^{108} + x^{99} + x^{96} + x^{63} + x^{60} + x^{51} + x^{48} + x^{15} + x^{12} + x^3 + 1,$$

and the initial terms are $[0, 0, 0, 1, 0, 0, 1, 0, 0, 1, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 1, 0, 0, 0, 0]$.

For $\phi(W^e, 1, 0)$:

$$p_0(x) = x^{126} + x^{117} + x^{111} + x^{102} + x^{93} + x^{87} + x^{84} + x^{81} + x^{78} + x^{75} + x^{72}$$

and the initial terms are $[0, 0, 0, 1, 0, 0, 1, 0, 0, 1, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0]$.

For $\phi(W^e, 1, 1)$:

[illegible]

For $\phi(M^o, 0, 0)$:

and the initial terms are $[1, 0, 0, 0, 0, 0, 1, 0, 0, 1, 0, 0, 1, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0]$.

For $\phi(M^o, 0, 1)$:

$$\begin{aligned} p_0(x) &= x^{132} + x^{123} + x^{114} + x^{111} + x^{90} + x^{87} + x^{81} + x^{78} + x^{57} + x^{54} + x^{45} \\ &\quad + x^{36}, \\ p_3(x) &= x^{111} + x^{108} + x^{105} + x^{102} + x^{87} + x^{84} + x^{81} + x^{78} + x^{63} + x^{60} + x^{57} \\ &\quad + x^{54}, \\ p_6(x) &= x^{114} + x^{108} + x^{102} + x^{96} + x^{78} + x^{72} + x^{54} + x^{48} + x^{42} + x^{36}, \end{aligned}$$

$$p_9(x) = x^{117} + x^{114} + x^{69} + x^{66} + x^{21} + x^{18},$$

$$p_{12}(x) = x^{120} + x^{108} + x^{96} + x^{72} + x^{60} + x^{48} + x^{24} + x^{12} + 1,$$

and the initial terms are $[0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 1, 0]$.

For $\phi(M^o, 1, 0)$:

$$p_0(x) = x^{126} + x^{123} + x^{120} + x^{117} + x^{108} + x^{105} + x^{102} + x^{99} + x^{96} + x^{87} \\ + x^{84} + x^{81} + x^{72} + x^{69} + x^{60} + x^{54} + x^{48} + x^{45} + x^{36},$$

$$p_3(x) = x^{123} + x^{120} + x^{117} + x^{114} + x^{111} + x^{108} + x^{105} + x^{102} + x^{99} + x^{96} \\ + x^{93} + x^{90} + x^{87} + x^{84} + x^{81} + x^{78} + x^{75} + x^{72} + x^{69} + x^{66} + x^{63} \\ + x^{60} + x^{57} + x^{54},$$

$$p_6(x) = x^{126} + x^{120} + x^{102} + x^{96} + x^{90} + x^{84} + x^{78} + x^{72} + x^{66} + x^{60} + x^{42} \\ + x^{36},$$

$$p_9(x) = x^{129} + x^{126} + x^{117} + x^{114} + x^{81} + x^{78} + x^{69} + x^{66} + x^{33} + x^{30} + x^{21} \\ + x^{18},$$

$$p_{12}(x) = x^{132} + x^{96} + x^{84} + x^{48} + x^{36} + 1,$$

and the initial terms are $[0, 0, 0, 1, 0, 0, 1, 0, 0, 1, 0, 0, 1, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 1, 0, 0, 1, 0, 0]$.

For $\phi(M^o, 1, 1)$:

$$p_0(x) = x^{126} + x^{120} + x^{111} + x^{90} + x^{81} + x^{72} + x^{69} + x^{66} + x^{63} + x^{60} + x^{57} \\ + x^{51} + x^{48} + x^{45} + x^{42} + x^{39} + x^{36},$$

$$p_3(x) = x^{123} + x^{105} + x^{96} + x^{93} + x^{90} + x^{87} + x^{84} + x^{81} + x^{72} + x^{69} + x^{66} \\ + x^{63} + x^{60} + x^{57} + x^{51} + x^{48} + x^{45} + x^{42} + x^{39} + x^{36},$$

$$p_6(x) = x^{123} + x^{108} + x^{105} + x^{90} + x^{87} + x^{81} + x^{78} + x^{75} + x^{72} + x^{69} + x^{63} \\ + x^{57} + x^{54} + x^{51} + x^{45} + x^{39} + x^{36} + x^{30} + x^{21} + x^{18} + x^3 + 1,$$

$$p_9(x) = x^{123} + x^{120} + x^{75} + x^{72} + x^{27} + x^{24},$$

$$p_{12}(x) = x^{123} + x^{120} + x^{111} + x^{108} + x^{99} + x^{96} + x^{75} + x^{72} + x^{63} + x^{60} + x^{51} \\ + x^{48} + x^{27} + x^{24} + x^{15} + x^{12} + x^3 + 1,$$

and the initial terms are $[0, 0, 0, 0, 0, 0, 1, 0, 0, 1, 0, 0, 0, 0, 0, 1, 0, 0, 1, 0, 0, 0, 0, 0, 1, 0, 0, 1, 0, 0, 0, 0, 0, 1, 0, 0, 1, 0, 0, 1, 0, 0]$.

For $\phi(W^o, 0, 0)$:

$$p_0(x) = x^{126} + x^{123} + x^{120} + x^{111} + x^{108} + x^{105} + x^{96} + x^{93} + x^{90} + x^{81} \\ + x^{78} + x^{72} + x^{69} + x^{66} + x^{57} + x^{45} + x^{42} + x^{39} + x^{36},$$

$$p_3(x) = x^{123} + x^{117} + x^{114} + x^{105} + x^{99} + x^{87} + x^{84} + x^{81} + x^{75} + x^{63} + x^{60} \\ + x^{57} + x^{45} + x^{42} + x^{39} + x^{36},$$

$$p_6(x) = x^{123} + x^{117} + x^{114} + x^{108} + x^{102} + x^{99} + x^{96} + x^{90} + x^{84} + x^{75} + x^{72} \\ + x^{69} + x^{60} + x^{51} + x^{42} + x^{30} + x^{27} + x^{24} + x^{21} + x^{18} + x^3 + 1,$$

$$p_9(x) = x^{123} + x^{120} + x^{75} + x^{72} + x^{27} + x^{24},$$

$$p_{12}(x) = x^{123} + x^{120} + x^{111} + x^{108} + x^{99} + x^{96} + x^{75} + x^{72} + x^{63} + x^{60} + x^{51} \\ + x^{48} + x^{27} + x^{24} + x^{15} + x^{12} + x^3 + 1,$$

and the initial terms are $[1, 0, 0, 0, 0, 0, 1, 0, 0, 1, 0, 0, 1, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0]$.

For $\phi(W^o, 0, 1)$:

$$\begin{aligned}
p_0(x) &= x^{126} + x^{123} + x^{120} + x^{117} + x^{108} + x^{105} + x^{102} + x^{99} + x^{96} + x^{87} \\
&\quad + x^{84} + x^{81} + x^{72} + x^{69} + x^{60} + x^{54} + x^{48} + x^{45} + x^{36}, \\
p_3(x) &= x^{123} + x^{120} + x^{117} + x^{114} + x^{111} + x^{108} + x^{105} + x^{102} + x^{99} + x^{96} \\
&\quad + x^{93} + x^{90} + x^{87} + x^{84} + x^{81} + x^{78} + x^{75} + x^{72} + x^{69} + x^{66} + x^{63} \\
&\quad + x^{60} + x^{57} + x^{54}, \\
p_6(x) &= x^{126} + x^{120} + x^{102} + x^{96} + x^{90} + x^{84} + x^{78} + x^{72} + x^{66} + x^{60} + x^{42} \\
&\quad + x^{36}, \\
p_9(x) &= x^{129} + x^{126} + x^{117} + x^{114} + x^{81} + x^{78} + x^{69} + x^{66} + x^{33} + x^{30} + x^{21} \\
&\quad + x^{18}, \\
p_{12}(x) &= x^{132} + x^{96} + x^{84} + x^{48} + x^{36} + 1,
\end{aligned}$$

and the initial terms are $[0, 0, 0, 1, 0, 0, 1, 0, 0, 1, 0, 0, 1, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 1, 0]$.

For $\phi(W^o, 1, 0)$:

$$\begin{aligned} p_0(x) &= x^{132} + x^{123} + x^{114} + x^{111} + x^{90} + x^{87} + x^{81} + x^{78} + x^{57} + x^{54} + x^{45} \\ &\quad + x^{36}, \\ p_3(x) &= x^{111} + x^{108} + x^{105} + x^{102} + x^{87} + x^{84} + x^{81} + x^{78} + x^{63} + x^{60} + x^{57} \\ &\quad + x^{54}, \\ p_6(x) &= x^{114} + x^{108} + x^{102} + x^{96} + x^{78} + x^{72} + x^{54} + x^{48} + x^{42} + x^{36}, \\ p_9(x) &= x^{117} + x^{114} + x^{69} + x^{66} + x^{21} + x^{18}, \\ p_{12}(x) &= x^{120} + x^{108} + x^{96} + x^{72} + x^{60} + x^{48} + x^{24} + x^{12} + 1, \end{aligned}$$

and the initial terms are $[0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 1, 0]$.

For $\phi(W^o, 1, 1)$:

$$\begin{aligned}
p_0(x) &= x^{126} + x^{120} + x^{111} + x^{90} + x^{81} + x^{72} + x^{69} + x^{66} + x^{63} + x^{60} + x^{57} \\
&\quad + x^{51} + x^{48} + x^{45} + x^{42} + x^{39} + x^{36}, \\
p_3(x) &= x^{123} + x^{105} + x^{96} + x^{93} + x^{90} + x^{87} + x^{84} + x^{81} + x^{72} + x^{69} + x^{66} \\
&\quad + x^{63} + x^{60} + x^{57} + x^{51} + x^{48} + x^{45} + x^{42} + x^{39} + x^{36}, \\
p_6(x) &= x^{123} + x^{108} + x^{105} + x^{90} + x^{87} + x^{81} + x^{78} + x^{75} + x^{72} + x^{69} + x^{63} \\
&\quad + x^{57} + x^{54} + x^{51} + x^{45} + x^{39} + x^{36} + x^{30} + x^{21} + x^{18} + x^3 + 1, \\
p_9(x) &= x^{123} + x^{120} + x^{75} + x^{72} + x^{27} + x^{24}, \\
p_{12}(x) &= x^{123} + x^{120} + x^{111} + x^{108} + x^{99} + x^{96} + x^{75} + x^{72} + x^{63} + x^{60} + x^{51} \\
&\quad + x^{48} + x^{27} + x^{24} + x^{15} + x^{12} + x^3 + 1,
\end{aligned}$$

and the initial terms are $[0, 0, 0, 0, 0, 0, 1, 0, 0, 1, 0, 0, 0, 0, 0, 1, 0, 0, 1, 0, 0, 0, 0, 0, 1, 0, 0, 1, 0, 0, 1, 0]$.

Below is the transition function and output function of an 2-automaton that generates $T = M_{0,0}^o$:

Transition function $(n, j) \mapsto \delta(n, j)$ ($\Lambda(n) := [\delta(n, 0), \delta(n, 1)]$):

n	$\Lambda(n)$	n	$\Lambda(n)$	n	$\Lambda(n)$	n	$\Lambda(n)$	n	$\Lambda(n)$
0	[1, 2]	13	[24, 25]	26	[24, 37]	39	[35, 52]	52	[46, 17]
1	[3, 4]	14	[26, 18]	27	[38, 4]	40	[53, 54]	53	[19, 18]
2	[5, 6]	15	[27, 2]	28	[37, 39]	41	[55, 8]	54	[21, 59]
3	[1, 7]	16	[7, 8]	29	[40, 20]	42	[56, 13]	55	[47, 43]
4	[8, 9]	17	[18, 28]	30	[41, 42]	43	[57, 30]	56	[42, 20]
5	[10, 11]	18	[18, 18]	31	[43, 44]	44	[35, 49]	57	[59, 23]
6	[12, 13]	19	[29, 30]	32	[6, 45]	45	[11, 53]	58	[28, 18]
7	[14, 15]	20	[8, 31]	33	[25, 39]	46	[52, 50]	59	[31, 51]
8	[4, 16]	21	[13, 11]	34	[14, 46]	47	[50, 35]		
9	[15, 17]	22	[32, 7]	35	[17, 47]	48	[33, 54]		
10	[18, 19]	23	[11, 33]	36	[48, 45]	49	[58, 44]		
11	[20, 21]	24	[34, 35]	37	[49, 50]	50	[47, 58]		
12	[22, 23]	25	[36, 2]	38	[9, 51]	51	[16, 38]		

Output function $n \mapsto \tau(n)$:

n	$\tau(n)$	n	$\tau(n)$	n	$\tau(n)$	n	$\tau(n)$	n	$\tau(n)$	n	$\tau(n)$	n	$\tau(n)$
0	0	9	1	18	0	27	1	36	0	45	0	54	0
1	0	10	0	19	1	28	1	37	1	46	0	55	0
2	0	11	0	20	0	29	1	38	1	47	0	56	0
3	0	12	1	21	0	30	0	39	0	48	0	57	0
4	0	13	0	22	1	31	0	40	1	49	1	58	1
5	0	14	0	23	0	32	1	41	0	50	0	59	0
6	1	15	1	24	0	33	0	42	0	51	0		
7	0	16	0	25	0	34	0	43	0	52	0		
8	0	17	0	26	0	35	0	44	0	53	1		

UNIVERSITÉ DE STRASBOURG, CNRS, IRMA UMR 7501, F-67000 STRASBOURG, FRANCE
Email address: guoniu.han@unistra.fr

SCHOOL OF MATHEMATICS AND STATISTICS, HUAZHONG UNIVERSITY OF SCIENCE AND TECHNOLOGY, WUHAN, PR CHINA
Email address: huyining@hust.edu.cn