

# CYCLIC RESULTANTS

CHRISTOPHER J. HILLAR

ABSTRACT. We characterize polynomials having the same set of nonzero cyclic resultants. Generically, for a polynomial  $f$  of degree  $d$ , there are exactly  $2^{d-1}$  distinct degree  $d$  polynomials with the same set of cyclic resultants as  $f$ . However, in the generic monic case, degree  $d$  polynomials are uniquely determined by their cyclic resultants. Moreover, two reciprocal (“palindromic”) polynomials giving rise to the same set of nonzero cyclic resultants are equal. In the process, we also prove a unique factorization result in semigroup algebras involving products of binomials. Finally, we discuss how our results yield algorithms for explicit reconstruction of polynomials from their cyclic resultants.

## 1. INTRODUCTION

The  $m$ -th cyclic resultant of a univariate polynomial  $f \in \mathbb{C}[x]$  is

$$r_m = \text{Res}(f, x^m - 1).$$

We are primarily interested here in the fibers of the map  $r : \mathbb{C}[x] \rightarrow \mathbb{C}^{\mathbb{N}}$  given by  $f \mapsto (r_m)_{m=0}^{\infty}$ . In particular, what are the conditions for two polynomials to give rise to the same set of cyclic resultants? For technical reasons, we will only consider polynomials  $f$  that do not have a root of unity as a zero. With this restriction, a polynomial will map to a set of all nonzero cyclic resultants. Our main result gives a complete answer to this question.

**Theorem 1.1.** *Let  $f$  and  $g$  be polynomials in  $\mathbb{C}[x]$ . Then,  $f$  and  $g$  generate the same sequence of nonzero cyclic resultants if and only if there exist  $u, v \in \mathbb{C}[x]$  with  $u(0) \neq 0$  and nonnegative integers  $l_1, l_2$  such that  $\deg(u) \equiv l_2 - l_1 \pmod{2}$ , and*

$$f(x) = (-1)^{l_2-l_1} x^{l_1} v(x) u(x^{-1}) x^{\deg(u)}$$

$$g(x) = x^{l_2} v(x) u(x).$$

*Remark 1.2.* All our results involving  $\mathbb{C}$  hold over any algebraically closed field of characteristic zero.

Although the theorem statement appears somewhat technical, we present a natural interpretation of the result. Suppose that  $g(x) = x^{l_2} v(x) u(x)$  is a factorization as above of a polynomial  $g$  with nonzero cyclic resultants. Then, another polynomial  $f$  giving rise to this same sequence of resultants is obtained from  $v$  by multiplication with the reversal  $u(x^{-1}) x^{\deg(u)}$  of  $u$  and a factor  $(-1)^{\deg(u)} x^{l_1}$  in which  $l_1 \equiv l_2 - \deg(u) \pmod{2}$ . In other words,  $f(x) = (-1)^{\deg(u)} x^{l_1} v(x) u(x^{-1}) x^{\deg(u)}$ , and all such  $f$  must arise in this manner.

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1991 *Mathematics Subject Classification.* Primary 11B83, 14Q99; Secondary 15A15, 20M25.

*Key words and phrases.* cyclic resultant, binomial factorization, group rings, toral endomorphisms.

This work is supported under a National Science Foundation Graduate Research Fellowship.

**Example 1.3.** One can check that the polynomials

$$\begin{aligned} f(x) &= x^3 - 10x^2 + 31x - 30 \\ g(x) &= 15x^5 - 38x^4 + 17x^3 - 2x^2 \end{aligned}$$

both generate the same cyclic resultants. This follows from the factorizations

$$\begin{aligned} f(x) &= (x - 2)(15x^2 - 8x + 1) \\ g(x) &= x^2(x - 2)(x^2 - 8x + 15). \quad \square \end{aligned}$$

One motivation for the study of cyclic resultants comes from the theory of dynamical systems. Sequences of the form  $r_m$  arise as the cardinalities of sets of periodic points for toral endomorphisms. Let  $A$  be a  $d$ -by- $d$  integer matrix and let  $X = \mathbb{T}^d = \mathbb{R}^d/\mathbb{Z}^d$  denote the  $d$ -dimensional additive torus. Then, the matrix  $A$  acts on  $X$  by multiplication mod 1; that is, it defines a map  $T : X \rightarrow X$  given by

$$T(\mathbf{x}) = A\mathbf{x} \pmod{\mathbb{Z}^d}.$$

Let  $\text{Per}_m(T) = \{\mathbf{x} \in \mathbb{T}^d : T^m(\mathbf{x}) = \mathbf{x}\}$  be the set of points fixed under the map  $T^m$ . Under the ergodicity condition that no eigenvalue of  $A$  is a root of unity, it follows (see [3]) that

$$|r_m(f)| = |\text{Per}_m(T)| = |\det(A^m - I)|,$$

in which  $I$  is the  $d$ -by- $d$  identity matrix, and  $f$  is the characteristic polynomial of  $A$ . As a consequence of our results, we characterize when the sequence  $|\text{Per}_m(T)|$  determines the spectrum of the linear map  $A$  lifting  $T$  (see Corollary 1.13).

In connection with number theory, cyclic resultants were also studied by Pierce and Lehmer [3] in the hope of using them to produce large primes. As a simple example, the Mersenne numbers  $M_m = 2^m - 1$  arise as cyclic resultants of the polynomial  $f(x) = x - 2$ . Indeed, the map  $T(x) = 2x \pmod{1}$  has precisely  $M_m$  points of period  $m$ . Further motivation comes from knot theory [11], Lagrangian mechanics [5, 7], and, more recently, in the study of amoebas of varieties [10] and quantum computing [8].

The principal result in the direction of our main characterization theorem was discovered by Fried [4] although certain implications of Fried's result were known to Stark [2]. Our approach is a refinement and generalization of the one found in [4]. Given a polynomial  $f = a_0x^d + a_1x^{d-1} + \dots + a_d$  of degree  $d$ , the *reversal* of  $f$  is the polynomial  $x^d f(1/x)$ . Additionally,  $f$  is called *reciprocal* if  $a_i = a_{d-i}$  for  $0 \leq i \leq d$  (sometimes such a polynomial is called *palindromic*). Alternatively,  $f$  is reciprocal if it is equal to its own reversal. Fried's result may be stated as follows. It will be a corollary of Theorem 1.8 below (the real version of Theorem 1.1).

**Corollary 1.4** (Fried). *Let  $p(x) = a_0x^d + \dots + a_{d-1}x + a_d \in \mathbb{R}[x]$  be a real reciprocal polynomial of even degree  $d$  with  $a_0 > 0$ , and let  $r_m$  be the  $m$ -th cyclic resultants of  $p$ . Then,  $|r_m|$  uniquely determine this polynomial of degree  $d$  as long as the  $r_m$  are never 0.*

The following is a direct corollary of our main theorem to the generic case.

**Corollary 1.5.** *Let  $g$  be a generic polynomial in  $\mathbb{C}[x]$  of degree  $d$ . Then, there are exactly  $2^{d-1}$  degree  $d$  polynomials with the same set of cyclic resultants as  $g$ .*

*Proof.* If  $g$  is generic, then  $g$  will not have a root of unity as a zero nor will  $g(0) = 0$ . Theorem 1.1, therefore, implies that any other degree  $d$  polynomial  $f \in \mathbb{C}[x]$  giving rise to the same set of cyclic resultants is determined by choosing an even cardinality subset of the roots of  $g$ . Such polynomials will be distinct since  $g$  is generic. Since there are  $2^d$  subsets of the roots of  $g$  and half of them have even cardinality, the theorem follows.  $\square$

**Example 1.6.** Let  $g(x) = (x-2)(x-3)(x-5) = x^3 - 10x^2 + 31x - 30$ . Then, there are  $2^{3-1} - 1 = 3$  other degree 3 polynomials with the same set of cyclic resultants as  $g$ . They are:

$$\begin{aligned} 15x^3 - 38x^2 + 17x - 2 \\ 10x^3 - 37x^2 + 22x - 3 \\ 6x^3 - 35x^2 + 26x - 5. \quad \square \end{aligned}$$

If one is interested in the case of generic monic polynomials, then Theorem 1.1 also implies the following uniqueness result.

**Corollary 1.7.** *The set of cyclic resultants determines  $g$  for generic monic  $g \in \mathbb{C}[x]$  of degree  $d$ .*

*Proof.* Again, since  $g$  is generic, it will not have a root of unity as a zero nor will  $g(0) = 0$ . Theorem 1.1 forces a constraint on the roots of  $g$  for there to be a different monic polynomial  $f$  with the same set of cyclic resultants as  $g$ . Namely, a subset of the roots of  $g$  has product 1, a non-generic situation.  $\square$

As to be expected, there are analogs of Theorem 1.1 and Corollary 1.7 to the real case involving absolute values.

**Theorem 1.8.** *Let  $f$  and  $g$  be polynomials in  $\mathbb{R}[x]$ . If  $f$  and  $g$  generate the same sequence of nonzero cyclic resultant absolute values, then there exist  $u, v \in \mathbb{C}[x]$  with  $u(0) \neq 0$  and nonnegative integers  $l_1, l_2$  such that*

$$\begin{aligned} f(x) &= \pm x^{l_1} v(x) u(x^{-1}) x^{\deg(u)} \\ g(x) &= x^{l_2} v(x) u(x). \end{aligned}$$

**Corollary 1.9.** *The set of cyclic resultant absolute values determines  $g$  for generic monic  $g \in \mathbb{R}[x]$  of degree  $d$ .*

The generic real case without the monic assumption is more subtle than that of Corollary 1.5. The difficulty is that we are restricted to polynomials in  $\mathbb{R}[x]$ . However, there is the following

**Corollary 1.10.** *Let  $g$  be a generic polynomial in the set of degree  $d$  elements of  $\mathbb{R}[x]$  with at most one real root. Then there are exactly  $2^{\lfloor d/2 \rfloor + 1}$  degree  $d$  polynomials in  $\mathbb{R}[x]$  with the same set of cyclic resultant absolute values as  $g$ .*

*Proof.* If  $d$  is even, then the hypothesis implies that all of the roots of  $g$  are nonreal. In particular, it follows from Theorem 1.8 (and genericity) that any other degree  $d$  polynomial  $f \in \mathbb{R}[x]$  giving rise to the same set of cyclic resultant absolute values is determined by choosing a subset of the  $d/2$  pairs of conjugate roots of  $g$  and a sign. This gives us a count of  $2^{d/2+1}$  distinct real polynomials. When  $d$  is odd,  $g$  has exactly one real root, and a similar counting argument gives us  $2^{\lfloor d/2 \rfloor + 1}$  for the number of distinct real polynomials in this case. This proves the corollary.  $\square$

A surprising consequence of this result is that the number of polynomials with equal sets of cyclic resultant absolute values can be significantly smaller than the number predicted by Corollary 1.5.

**Example 1.11.** Let  $g(x) = (x - 2)(x + i + 2)(x - i + 2) = x^3 + 2x^2 - 3x - 10$ . Then, there are  $2^{\lceil 3/2 \rceil + 1} - 1 = 7$  other degree 3 real polynomials with the same set of cyclic resultant absolute values as  $g$ . They are:

$$\begin{aligned} & -x^3 - 2x^2 + 3x + 10, \pm(-2x^3 - 7x^2 - 6x + 5), \\ & \pm(5x^3 - 6x^2 - 7x - 2), \pm(-10x^3 - 3x^2 + 2x + 1). \end{aligned}$$

It is important to realize that while

$$\begin{aligned} f(x) &= (1 - 2x)(1 + (i + 2)x)(x - i + 2) \\ &= (-4 - 2i)x^3 - (10 - i)x^2 + (2 + 2i)x + 2 - i \end{aligned}$$

has the same set of actual cyclic resultants (by Theorem 1.1), it does not appear in the count above since it is not in  $\mathbb{R}[x]$ .  $\square$

As an illustration of the usefulness of Theorem 1.1, we prove a uniqueness result involving cyclic resultants of reciprocal polynomials. Fried's result also follows in the same way using Theorem 1.8 in place of Theorem 1.1.

**Corollary 1.12.** *Let  $f$  and  $g$  be reciprocal polynomials with equal sets of nonzero cyclic resultants. Then,  $f = g$ .*

*Proof.* Let  $f$  and  $g$  be reciprocal polynomials having the same set of nonzero cyclic resultants. Applying Theorem 1.1, it follows that  $d = \deg(f) = \deg(g)$  and that

$$\begin{aligned} f(x) &= v(x)u(x^{-1})x^{\deg(u)} \\ g(x) &= v(x)u(x) \end{aligned}$$

( $l_1 = l_2 = 0$  since  $f(0), g(0) \neq 0$ ). But then,

$$\begin{aligned} \frac{u(x^{-1})}{u(x)} x^{\deg(u)} &= \frac{f(x)}{g(x)} \\ &= \frac{x^d f(x^{-1})}{x^d g(x^{-1})} \\ &= \frac{u(x)}{u(x^{-1})} x^{-\deg(u)}. \end{aligned}$$

In particular,  $u(x) = \pm u(x^{-1})x^{\deg(u)}$ . If  $u(x) = u(x^{-1})x^{\deg(u)}$ , then  $f = g$  as desired. In the other case, it follows that  $f = -g$ . But then  $\text{Res}(f, x - 1) = \text{Res}(g, x - 1) = -\text{Res}(f, x - 1)$  is a contradiction to  $f$  having all nonzero cyclic resultants. This completes the proof.  $\square$

We now state the application to toral endomorphisms discussed in the introduction.

**Corollary 1.13.** *Let  $T$  be an ergodic, toral endomorphism induced by a  $d$ -by- $d$  integer matrix  $A$ . If there is no subset of the eigenvalues of  $A$  with product  $\pm 1$ , then the sequence  $|\text{Per}_m(T)|$  determines the spectrum of the linear map that defines  $T$ .*

*Proof.* Suppose that  $T'$  is another toral endomorphism induced by an integral  $d$ -by- $d$  matrix  $B$  such that

$$|\mathrm{Per}_m(T)| = |\mathrm{Per}_m(T')|.$$

Let  $f$  and  $g$  be the characteristic polynomials of  $A$  and  $B$ , respectively. From the hypothesis of the corollary and the statement of Theorem 1.8, it follows that  $f$  and  $g$  must be equal. In particular, the eigenvalues of the matrices  $A$  and  $B$  coincide, completing the proof.  $\square$

*Remark 1.14.* We note that a more complete characterization is possible using the results of Theorem 1.8, however, the statement is more technical and not very enlightening.

When a degree  $d$  polynomial is uniquely determined by its sequence of cyclic resultants, it is natural to ask for an algorithm that performs the reconstruction. In several applications, moreover, explicit inversion using small numbers of resultants is desired (see, for instance, [7, 8]). In Section 5, we describe a method that inverts the map  $r$  using the first  $2^{d+1}$  cyclic resultants. Empirically, however, only  $d + 1$  resultants suffice, and a conjecture by Sturmfels and Zworski would imply that this is always the case. As evidence for this conjecture, we provide explicit reconstructions for several small examples.

The rest of the paper is organized as follows. In Section 2, we make a digression into the theory of semigroup algebras and binomial factorizations. The unique factorization result discussed there (Theorem 2.2) will form a crucial component in proving Theorem 1.1. The subsequent chapter deals with algebraic properties of cyclic resultants, and Section 5 concludes with proofs of our main cyclic resultant characterization theorems. Finally, in the last section, we discuss algorithms for reconstruction.

## 2. BINOMIAL FACTORIZATIONS

We now switch to the seemingly unrelated topic of binomial factorizations in semigroup algebras. The relationship to cyclic resultants will become clear later. Let  $A$  be a finitely generated abelian group and let  $a_1, \dots, a_n$  be distinguished generators of  $A$ . Let  $Q$  be the semigroup generated by  $a_1, \dots, a_n$ . The *semigroup algebra*  $\mathbb{C}[Q]$  is the  $\mathbb{C}$ -algebra with vector space basis  $\{\mathbf{s}^a : a \in Q\}$  and multiplication defined by  $\mathbf{s}^a \cdot \mathbf{s}^b = \mathbf{s}^{a+b}$ . Let  $L$  denote the kernel of the homomorphism  $\mathbb{Z}^n$  onto  $A$ . The *lattice ideal* associated with  $L$  is the following ideal in  $S = \mathbb{C}[x_1, \dots, x_n]$ :

$$I_L = \langle x^u - x^v : u, v \in \mathbb{N}^n \text{ with } u - v \in L \rangle.$$

It is well-known that  $\mathbb{C}[Q] \cong S/I_L$  (e.g. see [9]). We are primarily concerned here with certain kinds of factorizations in  $\mathbb{C}[Q]$ .

**Question 2.1.** *When is a product of binomials in  $\mathbb{C}[Q]$  equal to another product of binomials?*

The answer to this question turns out to be fundamental for the study of cyclic resultants. Our main result in this direction is a certain kind of unique factorization of binomials in  $\mathbb{C}[Q]$ .

**Theorem 2.2.** *Let  $\alpha \in \mathbb{C}$  and suppose that*

$$\mathbf{s}^a \prod_{i=1}^e (\mathbf{s}^{u_i} - \mathbf{s}^{v_i}) = \alpha \mathbf{s}^b \prod_{i=1}^f (\mathbf{s}^{x_i} - \mathbf{s}^{y_i})$$

are two factorizations of binomials in the ring  $\mathbb{C}[Q]$ . Furthermore, suppose that for each  $i$ , the difference  $u_i - v_i$  (resp.  $x_i - y_i$ ) has infinite order as an element of  $A$ . Then,  $\alpha = \pm 1$ ,  $e = f$ , and up to permutation, for each  $i$ , there are elements  $c_i, d_i \in Q$  such that  $s^{c_i}(s^{u_i} - s^{v_i}) = \pm s^{d_i}(s^{x_i} - s^{y_i})$ .

Of course, when each side has a factor of zero, the theorem fails. There are other obstructions, however, that make necessary the supplemental hypotheses concerning order. For example, when  $A = \mathbb{Z}/2\mathbb{Z}$ , we have  $\mathbb{C}[Q] = \mathbb{C}[A] \cong \mathbb{Q}[s]/\langle s^2 - 1 \rangle$ , and it is easily verified that

$$(1 - s)(1 - s) = 2(1 - s).$$

One might also wonder what happens when the binomials are not of the form  $s^u - s^v$ . The following example exhibits some of the difficulty in formulating a general statement.

**Example 2.3.**  $L = \{(0, b) \in \mathbb{Z}^2 : b \text{ is even}\}$ ,  $I_L = \langle s^2 - 1 \rangle \subseteq \mathbb{C}[s, t]$ ,  $A = \mathbb{Z} \oplus \mathbb{Z}/2\mathbb{Z}$ ,  $Q = \mathbb{N} \oplus \mathbb{Z}/2\mathbb{Z}$ . Then,

$$(1 - t^4) = (1 - st)(1 + st)(1 - ist)(1 + ist) = (1 - st^2)(1 + st^2)$$

are three different binomial factorizations of the same semigroup algebra element.  $\square$

We now are in a position to outline our strategy for characterizing those polynomials  $f$  and  $g$  having the same set of nonzero cyclic resultants (this strategy is similar to the one employed in [4]). Given a polynomial  $f$  and its sequence of  $r_m$ , we construct the generating function  $E_f(z) = \exp\left(-\sum_{m \geq 1} r_m \frac{z^m}{m}\right)$ . This series turns out to be rational with coefficients depending explicitly on the roots of  $f$ . Since  $f$  and  $g$  are assumed to have the same set of  $r_m$ , it follows that their corresponding rational functions  $E_f$  and  $E_g$  are equal. Let  $G$  be the (multiplicative) group of units of  $\mathbb{C}$ . Then, the divisors of these two rational functions are group ring elements in  $\mathbb{Z}[G]$ , and their equality forces a certain binomial group ring factorization that is analyzed explicitly. The main results in the introduction follow from this final analysis.

To prove our factorization result, we will pass to the full group algebra  $\mathbb{C}[A]$ . As above, we represent elements  $\tau \in \mathbb{C}[A]$  as  $\tau = \sum_{i=1}^m \alpha_i s^{g_i}$ , in which  $\alpha_i \in \mathbb{C}$  and  $g_i \in A$ . The following lemma is quite well-known.

**Lemma 2.4.** *If  $0 \neq \alpha \in \mathbb{C}$  and  $g \in A$  has infinite order, then  $1 - \alpha s^g \in \mathbb{C}[A]$  is not a zero-divisor.*

*Proof.* Let  $0 \neq \alpha \in \mathbb{C}$ ,  $g \in A$  and  $\tau = \sum_{i=1}^m \alpha_i s^{g_i} \neq 0$  be such that

$$\tau = \alpha s^g \tau = \alpha^2 s^{2g} \tau = \alpha^3 s^{3g} \tau = \dots$$

Suppose that  $\alpha_1 \neq 0$ . Then, the elements  $s^{g_1}, s^{g_1+g}, s^{g_1+2g}, \dots$  appear in  $\tau$  with nonzero coefficient, and since  $g$  has infinite order, these elements are all distinct. It follows, therefore, that  $\tau$  cannot be a finite sum, and this contradiction finishes the proof.  $\square$

Since the proof of the main theorem involves multiple steps, we record several facts that will be useful later. The first result is a verification of the factorization theorem for a special case.

**Lemma 2.5.** *Fix an abelian group  $C$ . Let  $\mathbb{C}[C]$  be the group algebra with  $\mathbb{C}$ -vector space basis given by  $\{\mathbf{s}^c : c \in C\}$  and set  $R = \mathbb{C}[C][t, t^{-1}]$ . Suppose that  $c_i, d_i, b \in C$ ,  $m_i, n_i$  are nonzero integers,  $q \in \mathbb{Z}$ , and  $z \in \mathbb{C}$  are such that*

$$\prod_{i=1}^e (1 - \mathbf{s}^{c_i} t^{m_i}) = z \mathbf{s}^b t^q \prod_{i=1}^f (1 - \mathbf{s}^{d_i} t^{n_i})$$

holds in  $R$ . Then,  $e = f$  and after a permutation, for each  $i$ , either  $\mathbf{s}^{c_i} t^{m_i} = \mathbf{s}^{d_i} t^{n_i}$  or  $\mathbf{s}^{c_i} t^{m_i} = \mathbf{s}^{-d_i} t^{-n_i}$ .

*Proof.* Let  $\text{sgn} : \mathbb{Z} \setminus \{0\} \rightarrow \{-1, 1\}$  denote the standard sign map  $\text{sgn}(n) = n/|n|$  and set  $\gamma = z \mathbf{s}^b t^q$ . Rewrite the left-hand side of the given equality as:

$$\prod_{i=1}^e (1 - \mathbf{s}^{c_i} t^{m_i}) = \prod_{\text{sgn}(m_i)=-1} -\mathbf{s}^{c_i} t^{m_i} \prod_{i=1}^e \left(1 - \mathbf{s}^{\text{sgn}(m_i)c_i} t^{|m_i|}\right).$$

Similarly for the right-hand side, we have:

$$\prod_{i=1}^f (1 - \mathbf{s}^{d_i} t^{n_i}) = \prod_{\text{sgn}(n_i)=-1} -\mathbf{s}^{d_i} t^{n_i} \prod_{i=1}^f \left(1 - \mathbf{s}^{\text{sgn}(n_i)d_i} t^{|n_i|}\right).$$

Next, set

$$\eta = \gamma \prod_{\text{sgn}(m_i)=-1} -\mathbf{s}^{-c_i} t^{-m_i} \prod_{\text{sgn}(n_i)=-1} -\mathbf{s}^{d_i} t^{n_i}$$

so that our original equation may be written as

$$\prod_{i=1}^e \left(1 - \mathbf{s}^{\text{sgn}(m_i)c_i} t^{|m_i|}\right) = \eta \prod_{i=1}^f \left(1 - \mathbf{s}^{\text{sgn}(n_i)d_i} t^{|n_i|}\right).$$

Comparing the lowest degree term (with respect to  $t$ ) on both sides, it follows that  $\eta = 1$ . It is enough, therefore, to prove the claim in the case when

$$(2.1) \quad \prod_{i=1}^e (1 - \mathbf{s}^{c_i} t^{m_i}) = \prod_{i=1}^f (1 - \mathbf{s}^{d_i} t^{n_i})$$

and the  $m_i, n_i$  are positive. Without loss of generality, suppose the lowest degree nonconstant term on both sides of (2.1) is  $t^{m_1}$  with coefficient  $-\mathbf{s}^{c_1} - \dots - \mathbf{s}^{c_u}$  on the left and  $-\mathbf{s}^{d_1} - \dots - \mathbf{s}^{d_v}$  on the right. Here,  $u$  (resp.  $v$ ) corresponds to the number of  $m_i$  (resp.  $n_i$ ) with  $m_i = m_1$  (resp.  $n_i = m_1$ ).

Since the set of distinct monomials  $\{\mathbf{s}^c : c \in C\}$  is a  $\mathbb{C}$ -vector space basis for the ring  $\mathbb{C}[C]$ , equality of the  $t^{m_1}$  coefficients above implies that  $u = v$  and that up to permutation,  $\mathbf{s}^{c_j} = \mathbf{s}^{d_j}$  for  $j = 1, \dots, u$  (here is where we use that the characteristic of  $\mathbb{C}$  is zero). Lemma 2.4 and induction complete the proof.  $\square$

**Lemma 2.6.** *Let  $P = (p_{ij})$  be a  $d$ -by- $n$  integer matrix such that every row has at least one nonzero integer. Then, there exists  $\mathbf{v} \in \mathbb{Z}^n$  such that the vector  $P\mathbf{v}$  does not contain a zero entry.*

*Proof.* Let  $P$  be a  $d$ -by- $n$  integer matrix as in the hypothesis of the lemma, and for  $h \in \mathbb{Z}$ , let  $\mathbf{v}_h = (1, h, h^2, \dots, h^{n-1})^T$ . Assume, by way of contradiction, that  $P\mathbf{v}$  contains a zero entry for all  $\mathbf{v} \in \mathbb{Z}^n$ . Then, in particular, this is true for all  $\mathbf{v}_h$  as



such that  $\phi(g_i), \phi(h_i) \neq 0$  for all  $i$ . The ring  $\mathbb{C}[A]$  may be embedded into the Laurent ring,  $R = \mathbb{C}[A][t, t^{-1}]$ , by way of

$$\psi \left( \sum_{i=1}^m \alpha_i \mathbf{s}^{a_i} \right) = \sum_{i=1}^m \alpha_i \mathbf{s}^{a_i} t^{\phi(a_i)}.$$

Write  $\eta = \alpha \mathbf{s}^b$ . Then, applying this homomorphism to the original factorization, we have

$$\prod_{i=1}^e (1 - \mathbf{s}^{g_i} t^{\phi(g_i)}) = \alpha \mathbf{s}^b t^{\phi(b)} \prod_{i=1}^f (1 - \mathbf{s}^{h_i} t^{\phi(h_i)}).$$

Lemma 2.5 now applies to give us that  $e = f$  and there is an integer  $p$  such that up to permutation,

- (1)  $g_i = h_i$  for  $i = 1, \dots, p$
- (2)  $g_i = -h_i$  for  $i = p+1, \dots, e$ .

We are therefore left with verifying statement (3) of the lemma. Using Lemma 2.4, we may cancel equal terms in our original factorization, leaving us with the following equation:

$$\begin{aligned} \prod_{i=p+1}^e (1 - \mathbf{s}^{g_i}) &= \eta \prod_{i=p+1}^e (1 - \mathbf{s}^{-g_i}) \\ &= \eta (-1)^{e-p} \prod_{i=p+1}^e \mathbf{s}^{-g_i} \prod_{i=p+1}^e (1 - \mathbf{s}^{g_i}). \end{aligned}$$

Finally, one more application of Lemma 2.4 gives us that  $\eta = (-1)^{e-p} \mathbf{s}^{g_{p+1} + \dots + g_e}$  as desired. This finishes the proof.  $\square$

We may now prove Theorem 2.2.

*Proof of Theorem 2.2.* Let

$$\mathbf{s}^a \prod_{i=1}^e (\mathbf{s}^{u_i} - \mathbf{s}^{v_i}) = \alpha \mathbf{s}^b \prod_{i=1}^f (\mathbf{s}^{x_i} - \mathbf{s}^{y_i})$$

be two factorizations in the ring  $\mathbb{C}[Q]$ . View this expression in  $\mathbb{C}[A]$  and factor each element of the form  $(\mathbf{s}^u - \mathbf{s}^v)$  as  $\mathbf{s}^u (1 - \mathbf{s}^{v-u})$ . By assumption, each such  $v - u$  has infinite order. Now, apply Lemma 2.8, giving us that  $\alpha = \pm 1$ ,  $e = f$ , and that after a permutation, for each  $i$  either  $\mathbf{s}^{v_i - u_i} = \mathbf{s}^{y_i - x_i}$  or  $\mathbf{s}^{v_i - u_i} = \mathbf{s}^{x_i - y_i}$ . It easily follows from this that for each  $i$ , there are elements  $c_i, d_i \in Q$  such that  $\mathbf{s}^{c_i} (\mathbf{s}^{u_i} - \mathbf{s}^{v_i}) = \pm \mathbf{s}^{d_i} (\mathbf{s}^{x_i} - \mathbf{s}^{y_i})$ . This completes the proof of the theorem.  $\square$

### 3. CYCLIC RESULTANTS AND RATIONAL FUNCTIONS

We begin with some preliminaries concerning cyclic resultants. Let  $f(x) = a_0 x^d + a_1 x^{d-1} + \dots + a_d$  be a degree  $d$  polynomial over  $\mathbb{C}$ , and let the companion matrix for  $f$  be given by:

$$A = \begin{bmatrix} 0 & 0 & \cdots & 0 & -a_d/a_0 \\ 1 & 0 & \cdots & 0 & -a_{d-1}/a_0 \\ 0 & 1 & \cdots & 0 & -a_{d-2}/a_0 \\ 0 & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 1 & -a_1/a_0 \end{bmatrix}.$$

Also, let  $I$  denote the  $d$ -by- $d$  identity matrix. Then, we may write [1, p. 77]

$$(3.1) \quad r_m = a_0^m \det(A^m - I).$$

This equation can also be expressed as,

$$(3.2) \quad r_m = a_0^m \prod_{i=1}^d (\alpha_i^m - 1),$$

in which  $\alpha_1, \dots, \alpha_d$  are the roots of  $f(x)$ .

Let  $e_i(y_1, \dots, y_d)$  be the  $i$ -th elementary symmetric function in the variables  $y_1, \dots, y_d$  (we set  $e_0 = 1$ ). Then, we know that  $a_i = (-1)^i a_0 e_i(\alpha_1, \dots, \alpha_d)$  and that

$$(3.3) \quad r_m = a_0^m \sum_{i=0}^d (-1)^i e_{d-i}(\alpha_1^m, \dots, \alpha_d^m).$$

We first record an auxiliary result.

**Lemma 3.1.** *Let  $F_k(z) = \prod_{1 \leq i_1 < \dots < i_k \leq d} (1 - a_0 \alpha_{i_1} \dots \alpha_{i_k} z)$  with  $F_0(z) = 1 - a_0 z$ .*

*Then,*

$$\sum_{m=1}^{\infty} a_0^m e_k(\alpha_1^m, \dots, \alpha_d^m) z^m = -z \cdot \frac{F'_k}{F_k},$$

*in which  $F'_k$  denotes  $\frac{dF_k}{dz}$ .*

*Proof.* For  $k = 0$ , the equation is easily verified. When  $k > 0$ , the calculation is still fairly straightforward:

$$\begin{aligned} \sum_{m=1}^{\infty} a_0^m e_k(\alpha_1^m, \dots, \alpha_d^m) z^m &= \sum_{m=1}^{\infty} \sum_{i_1 < \dots < i_k} a_0^m \alpha_{i_1}^m \dots \alpha_{i_k}^m \cdot z^m \\ &= \sum_{i_1 < \dots < i_k} \sum_{m=1}^{\infty} a_0^m \alpha_{i_1}^m \dots \alpha_{i_k}^m \cdot z^m \\ &= \sum_{i_1 < \dots < i_k} \frac{a_0 \alpha_{i_1} \dots \alpha_{i_k} z}{1 - a_0 \alpha_{i_1} \dots \alpha_{i_k} z} \\ &= \frac{-z \cdot \frac{d}{dz} \left[ \prod_{i_1 < \dots < i_k} (1 - a_0 \alpha_{i_1} \dots \alpha_{i_k} z) \right]}{\prod_{i_1 < \dots < i_k} (1 - a_0 \alpha_{i_1} \dots \alpha_{i_k} z)} \\ &= -z \cdot \frac{F'_k}{F_k}. \end{aligned}$$

□

We are now ready to state and prove the rationality result mentioned in Section 2.

**Lemma 3.2.**  *$R_f(z) = \sum_{m=1}^{\infty} r_m z^m$  is a rational function in  $z$ .*

*Proof.* We simply compute that

$$\begin{aligned} \sum_{m=1}^{\infty} r_m z^m &= \sum_{m=1}^{\infty} \sum_{i=0}^d (-1)^i a_0^m e_{d-i}(\alpha_1^m, \dots, \alpha_d^m) \cdot z^m \\ &= \sum_{i=0}^d (-1)^i \sum_{m=1}^{\infty} a_0^m e_{d-i}(\alpha_1^m, \dots, \alpha_d^m) \cdot z^m \\ &= -z \cdot \sum_{i=0}^d (-1)^i \cdot \frac{F'_{d-i}}{F_{d-i}}. \end{aligned}$$

□

Manipulating the expression for  $R_f(z)$  occurring in Lemma 3.2, we also have the following fact.

**Corollary 3.3.** *If  $d$  is even, let  $G_d = \frac{F_d F_{d-2} \cdots F_0}{F_{d-1} F_{d-3} \cdots F_1}$  and if  $d$  is odd, let  $G_d = \frac{F_d F_{d-2} \cdots F_1}{F_{d-1} F_{d-3} \cdots F_0}$ . Then,*

$$\sum_{m=1}^{\infty} r_m z^m = -z \frac{G'_d}{G_d}.$$

In particular, it follows that

$$(3.4) \quad \exp\left(-\sum_{m=1}^{\infty} r_m \frac{z^m}{m}\right) = G_d.$$

**Example 3.4.** Let  $f(x) = x^2 - 5x + 6 = (x-2)(x-3)$ . Then,  $r_m = (2^m - 1)(3^m - 1)$  and  $F_0(z) = 1 - z$ ,  $F_1(z) = (1 - 2z)(1 - 3z)$ ,  $F_2(z) = 1 - 6z$ . Thus,

$$R_f(z) = -z \left( \frac{F'_2}{F_2} - \frac{F'_1}{F_1} + \frac{F'_0}{F_0} \right) = \frac{6z}{1-6z} - \frac{2z}{1-2z} - \frac{3z}{1-3z} + \frac{z}{1-z}$$

and

$$\exp\left(-\sum_{m=1}^{\infty} r_m \frac{z^m}{m}\right) = \frac{(1-6z)(1-z)}{(1-2z)(1-3z)}. \quad \square$$

Following [4], we discuss how to deal with absolute values in the real case. Let  $f \in \mathbb{R}[x]$  have degree  $d$  such that the  $r_m$  as defined above are all nonzero. We examine the sign of  $r_m$  using equation (3.2). First notice that a complex conjugate pair of roots of  $f$  does not affect the sign of  $r_m$ . A real root  $\alpha$  of  $f$  contributes a sign factor of  $+1$  if  $\alpha > 1$ ,  $-1$  if  $-1 < \alpha < 1$ , and  $(-1)^m$  if  $\alpha < -1$ . Let  $E$  be the number of zeroes of  $f$  in  $(-1, 1)$  and let  $D$  be the number of zeroes in  $(-\infty, -1)$ . Also, set  $\epsilon = (-1)^E$  and  $\delta = (-1)^D$ . Then, it follows that

$$(3.5) \quad \frac{r_m}{|r_m|} = \epsilon \cdot \delta^m.$$

In particular,

$$(3.6) \quad |r_m| = \epsilon (\delta a_0)^m \prod_{i=1}^d (\alpha_i^m - 1).$$

In other words, the sequence of  $|r_m|$  is obtained by multiplying each cyclic resultant of the polynomial  $\tilde{f} := \delta f = \delta a_0 x^d + \delta a_1 x^{d-1} + \cdots + \delta a_d$  by  $\epsilon$ . Denoting by  $\tilde{G}_d$  the rational function determined by  $\tilde{f}$  as in (3.3), it follows that

$$(3.7) \quad \exp \left( - \sum_{m=1}^{\infty} |r_m| \frac{z^m}{m} \right) = \left( \tilde{G}_d \right)^\epsilon.$$

#### 4. PROOFS OF THE MAIN THEOREMS

Let  $G$  be the multiplicative group generated by the roots  $\alpha_1, \dots, \alpha_d$  of a polynomial  $f$  for which  $f(0) \neq 0$ . We deal with the case when zero is a root of  $f$  later. Because of the multiplicative structure of  $G$ , we represent vector space basis elements of the group ring  $\mathbb{C}[G]$  as  $[\alpha]$ ,  $\alpha \in G$ ; multiplication is given by  $[\alpha] \cdot [\beta] = [\alpha\beta]$ . The divisor (in  $\mathbb{C}[G]$ ) of the rational function  $G_d$  defined by Corollary 3.3 is

$$(4.1) \quad \begin{aligned} & (-1)^{d+1} \left( \sum_{k \text{ odd}} \sum_{i_1 < \cdots < i_k} \left[ (a_0 \alpha_{i_1} \cdots \alpha_{i_k})^{-1} \right] - \sum_{k \text{ even}} \sum_{i_1 < \cdots < i_k} \left[ (a_0 \alpha_{i_1} \cdots \alpha_{i_k})^{-1} \right] \right) \\ &= [a_0^{-1}] \prod_{i=1}^d ([\alpha_i^{-1}] - [1]). \end{aligned}$$

Let us remark that for ease of presentation above, when  $k = 0$ , we have assigned

$$\sum_{i_1 < \cdots < i_k} \left[ (a_0 \alpha_{i_1} \cdots \alpha_{i_k})^{-1} \right] = [a_0^{-1}],$$

which corresponds to the factor of  $F_0(z) = 1 - a_0 z$  in  $G_d$ .

Now, suppose that  $f = x^l h$  in which  $h(0) \neq 0$  and  $h$  has degree  $d$ . Then, from (3.2), the cyclic resultants of  $f$  are given by  $(-1)^l r_m(h)$ . Examining equation (3.3) following Corollary 3.3, it follows that the divisor of  $G_d$  for  $f$  is given by the divisor of the rational function

$$\exp \left( - \sum_{m=1}^{\infty} r_m(f) \frac{z^m}{m} \right) = \left[ \exp \left( - \sum_{m=1}^{\infty} r_m(h) \frac{z^m}{m} \right) \right]^{(-1)^l}.$$

Let  $\alpha_1, \dots, \alpha_d$  be the roots of  $h$ . By the discussion above, it therefore follows that the divisor of  $G_d$  for  $f$  is

$$(-1)^l [a_0^{-1}] \prod_{i=1}^d ([\alpha_i^{-1}] - [1]).$$

With this computation in hand, we now prove our main theorems.

*Proof of Theorem 1.1.* Let  $f$  and  $g$  be polynomials as in the hypothesis, and suppose that the multiplicity of 0 as a root of  $f$  (resp.  $g$ ) is  $l_1$  (resp.  $l_2$ ). Then,  $f(x) = x^{l_1}(a_0 x^{d_1} + \cdots + a_{d_1})$  and  $g(x) = x^{l_2}(b_0 x^{d_2} + \cdots + b_{d_2})$  in which  $a_0$  and  $b_0$  are not 0. Let  $\alpha_1, \dots, \alpha_{d_1}$  and  $\beta_1, \dots, \beta_{d_2}$  be the nonzero roots of  $f$  and  $g$ , respectively, and let  $G$  be the multiplicative group generated by these elements. Since  $f$  and  $g$  both generate the same sequence of cyclic resultants, it follows that the

divisor (in the group ring  $\mathbb{C}[G]$ ) of their corresponding rational functions (see (3.4)) are equal. By above, such divisors factor, giving us that

$$(-1)^{d_1+l_1} [a_0^{-1}] \prod_{i=1}^{d_1} ([1] - [\alpha_i^{-1}]) = (-1)^{d_2+l_2} [b_0^{-1}] \prod_{i=1}^{d_2} ([1] - [\beta_i^{-1}]).$$

Since we have assumed that  $f$  and  $g$  generate a set of nonzero cyclic resultants, neither of them can have a root of unity as a zero. Therefore, Lemma 2.8 applies to give us that  $d := d_1 = d_2$  and that up to a permutation, there is a nonnegative integer  $p$  such that

- (1)  $\alpha_i = \beta_i$  for  $i = 1, \dots, p$
- (2)  $\alpha_i = \beta_i^{-1}$  for  $i = p+1, \dots, d$
- (3)  $(-1)^{d-p} = (-1)^{l_2-l_1}$ ,  $a_0 b_0^{-1} = \beta_{p+1} \cdots \beta_d$ .

Set  $u(x) = (x - \beta_{p+1}) \cdots (x - \beta_d)$  which has  $\deg(u) \equiv l_2 - l_1 \pmod{2}$ , and let  $v(x) = b_0(x - \beta_1) \cdots (x - \beta_p)$  (note that if  $p = 0$ , then  $v(x) = b_0$ ) so that  $g(x) = x^{l_2} v(x) u(x)$ . Now,

$$u(x^{-1}) x^{\deg(u)} = (-1)^{d-p} \beta_{p+1} \cdots \beta_d (x - \beta_{p+1}^{-1}) \cdots (x - \beta_d^{-1}),$$

and thus

$$\begin{aligned} f(x) &= x^{l_1} a_0 b_0^{-1} v(x) (x - \beta_{p+1}^{-1}) \cdots (x - \beta_d^{-1}) \\ &= (-1)^{l_2-l_1} x^{l_1} v(x) u(x^{-1}) x^{\deg(u)}. \end{aligned}$$

Finally, the converse is straightforward from (3.2), completing the proof of the theorem.  $\square$

The proof of Theorem 1.8 is similar, employing equation (3.7) in place of (3.4).

*Proof of Theorem 1.8.* Since multiplication of a real polynomial by a power of  $x$  does not change the absolute value of a cyclic resultant, we may assume  $f, g \in \mathbb{R}[x]$  have nonzero roots. The result now follows from (3.7) and the argument used to prove the if-direction of Theorem 1.1.  $\square$

## 5. RECONSTRUCTING DYNAMICAL SYSTEMS FROM THEIR ZETA FUNCTIONS

In this section, we describe how to explicitly reconstruct a polynomial from its cyclic resultants. For an ergodic toral endomorphism as in the introduction, sequences  $|r_m|$  correspond to cardinalities of sets of periodic points. In particular, the *zeta function*,

$$Z(T, z) = \exp \left( - \sum_{m=1}^{\infty} |\text{Per}_m(T)| \frac{z^m}{m} \right),$$

of the dynamical system in question is simply another way of writing equation (3.7).

In many of the applications [2, 7, 8, 11], the defining polynomial is reciprocal, and the techniques discussed here restrict easily to this special case. Furthermore, since reciprocal polynomials are uniquely determined without any genericity assumptions (see Corollary 1.4 and Corollary 1.12), the computational organization is simpler.

Let  $f(x) = a_0 x^d + a_1 x^{d-1} + \cdots + a_d$  be a degree  $d$  polynomial with indeterminate coefficients  $a_i$ . We distinguish between two cases. In the first situation, the variable  $a_0$  is replaced by 1 so that  $f$  is monic; while in the second, we set  $a_i = a_{d-i}$  for  $i = 1, \dots, d$  so that  $f$  is reciprocal.

Although the results mentioned in this paper only imply that the full sequence of cyclic resultants determine  $f$  when it is (generic) monic or reciprocal, a finite number of resultants is sufficient. Specifically, as detailed in forthcoming work [6], it is shown that  $2^{d+1}$  resultants are enough. Empirical evidence suggests that this is far from tight, and a conjecture of Sturmfels and Zworski asserts the following.

**Conjecture 5.1.** *A generic monic polynomial  $f(x) \in \mathbb{C}[x]$  of degree  $d$  is determined by its first  $d+1$  cyclic resultants. Moreover, if  $f$  is (non-monic) reciprocal of even degree  $d$ , then the number of resultants needed for inversion is given by  $d/2 + 2$ .*

A straightforward algorithm for inverting  $N$  cyclic resultants is as follows. Its correctness when  $N = 2^{d+1}$  follows from [1] and the results of [6].

**Algorithm 5.2.** (Specific reconstruction of a polynomial from its cyclic resultants)

Input: Positive integer  $d$  and a sequence of  $r_1, \dots, r_N \in \mathbb{C}$ .

Output: The coefficients  $a_i$  ( $i = 0, \dots, d$ ) corresponding to  $f$ .

- (1) Compute a lexicographic Gröbner basis  $\mathcal{G}$  for the ideal

$$I = \langle r_1 - \text{Res}(f, x - 1), \dots, r_N - \text{Res}(f, x^N - 1) \rangle.$$

- (2) Solve the resulting triangular system of equations for  $a_i$  using back substitution.

□

If the data are given in terms of cyclic resultant absolute values (for the real case), then more care must be taken in implementing Algorithm 5.2. Examining expression (3.5), there are 2 possible sequences of viable  $r_m$  that come from a given sequence of (generically generated) cyclic resultant absolute values  $|r_m|$ ; they are  $\{|r_m|\}$  and  $\{-|r_m|\}$ . By the uniqueness in Corollaries 1.7 and 1.9, however, only one of these sequences can come from a monic polynomial. Therefore, the corresponding modification is to run Algorithm 5.2 on both these inputs. For one of these sequences, it will generate the Gröbner basis  $\langle 1 \rangle$ ; while for the other, it will output the desired reconstruction.

Finding “universal” equations expressing the coefficients  $a_i$  in terms of the resultants  $r_i$  is also possible using a similar strategy.

**Algorithm 5.3.** (Formal reconstruction of a polynomial from its cyclic resultants)

Input: Positive integers  $d$  and  $N$ .

Output: Equations expressing  $a_i$  ( $i = 0, \dots, d$ ) parameterized by  $r_1, \dots, r_N$ .

- (1) Let  $R = \mathbb{Q}[a_0, \dots, a_d, r_1, \dots, r_N]$  and let  $\prec$  be any elimination term order with  $\{a_i\} \prec \{r_j\}$ .
- (2) Compute the reduced Gröbner basis  $\mathcal{G}$  for the ideal

$$I = \langle r_1 - \text{Res}(f, x - 1), \dots, r_N - \text{Res}(f, x^N - 1) \rangle.$$

- (3) Output a triangular system of equations for  $a_i$  in terms of the  $r_i$ .

□

A few remarks concerning Algorithm 5.3 are in order. If the  $a_i$  are indeterminates, a monic polynomial with coefficients  $a_i$  will be generic. Therefore, the first  $N = 2^{d+1}$  cyclic resultants of  $f$  will determine it as a polynomial in  $x$  over an algebraic closure of  $\mathbb{Q}(a_1, \dots, a_d)$ . It then follows from general theory (for instance, quantifier elimination for ACF, algebraically closed fields) that each  $a_i$  can

be expressed as a rational function in the  $r_i$  ( $i = 1, \dots, N$ ). The same result holds for reciprocal polynomials with indeterminate coefficients. It is an interesting and difficult problem to determine these rational functions for a given  $d$ . As motivation for future work on this problem, we use Algorithm 5.3 to find these expressions explicitly for several small cases.

When  $f = a_0x + a_1$  is linear, we need only two nonzero cyclic resultants to recover the coefficients  $a_0, a_1$ . An inversion is given by the formulae:

$$a_0 = \frac{r_2^2 - r_1}{2r_1}, \quad a_1 = \frac{-r_1^2 - r_2}{2r_1}.$$

In the quadratic case, a monic  $f = x^2 + a_1x + a_2$  is also determined by two nonzero resultants:

$$a_1 = \frac{r_1^2 - r_2}{2r_1}, \quad a_2 = \frac{r_1^2 - 2r_1 + r_2}{2r_1}.$$

When  $f = x^3 + a_1x^2 + a_2x + a_3$  has degree three, four resultants suffice, and inversion is given by:

$$\begin{aligned} a_1 &= \frac{-12r_2r_1^3 - 12r_1r_2^2 + 3r_2^3 - r_2r_1^4 - 8r_2r_1r_3 + 6r_1^2r_4}{24r_2r_1^2}, \\ a_2 &= \frac{-r_1^2 - 2r_1 + r_2}{2r_1}, \\ a_3 &= \frac{-3r_2^3 + r_2r_1^4 + 8r_2r_1r_3 - 6r_1^2r_4}{24r_1^2r_2}. \end{aligned}$$

Reconstruction for  $d = 4$  is also possible using five resultants, however, the expressions are too cumbersome to list here.

As a final example, we describe the reconstruction of a degree 6 monic, reciprocal polynomial  $f = x^6 + a_1x^5 + a_2x^4 + a_3x^3 + a_2x^2 + a_1x + 1$  from its first four cyclic resultants:

$$\begin{aligned} P &= -540r_1^2r_2r_4 - 13824r_1^3r_2 + r_1^6r_2 + 27r_2^3r_1^2 + 9r_1^4r_2^2 + 27r_2^4 - 432r_1^3r_2^2 - \\ &648r_1r_2^3 - 72r_1^5r_2 - 448r_3r_1^3r_2 + 192r_3r_1r_2^2 + 108r_1^4r_4 + 1536r_1^2r_2r_3 + \\ &2592r_1^3r_4 + 1728r_1^4r_2 + 5184r_1^2r_2^2, \end{aligned}$$

$$Q = r_1^2(-16r_3r_2 + 9r_4r_1),$$

$$\begin{aligned} R &= -648r_1r_2^3 + 27r_2^3r_1^2 + 27r_2^4 - 576r_3r_1r_2^2 + 2592r_1^3r_4 + r_1^6r_2 - 72r_1^5r_2 + \\ &9r_1^4r_2^2 + 1728r_1^4r_2 - 432r_1^3r_2^2 + 320r_3r_1^3r_2 - 324r_1^4r_4 - 13824r_1^3r_2 + \\ &5184r_1^2r_2^2 + 1536r_1^2r_2r_3 - 108r_1^2r_2r_4, \end{aligned}$$

$$a_1 = \frac{1}{192}P/Q, \quad a_2 = \frac{-4r_1 + r_1^2 + r_2}{4r_1}, \quad a_3 = \frac{-1}{96}R/Q.$$

## 6. ACKNOWLEDGEMENT

We would like to thank Bernd Sturmfels and Maciej Zworski for bringing this problem to our attention and for useful discussions. We also thank the anonymous referees for helpful comments that improved exposition.

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DEPARTMENT OF MATHEMATICS, UNIVERSITY OF CALIFORNIA, BERKELEY, CA 94720.

*E-mail address:* `chillar@math.berkeley.edu`