Diagonal asymptotics for symmetric rational functions via ACSV

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Abstract

We consider asymptotics of power series coefficients of rational functions of the form $1/Q$ where Q is a symmetric multilinear polynomial. We review a number of such cases from the literature, chiefly concerned either with positivity of coefficients or diagonal asymptotics. We then analyze coefficient asymptotics using ACSV (Analytic Combinatorics in Several Variables) methods. While ACSV sometimes requires considerable overhead and geometric computation, in the case of symmetric multilinear rational functions there are some reductions that streamline the analysis. Our results include diagonal asymptotics across entire classes of functions, for example the general 3-variable case and the Gillis-Reznick-Zeilberger (GRZ) case, where the denominator in terms of elementary symmetric functions is $1 - e_1 + ce_d$ in any number d of variables. The ACSV analysis also explains a discontinuous drop in exponential growth rate for the GRZ class at the parameter value $c = (d-1)^{d-1}$, previously observed for $d = 4$ only by separately computing diagonal recurrences for critical and noncritical values of c.

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1 Introduction

We study the power series coefficients of rational functions of the form $F(x_1, \ldots, x_d) = 1/Q(x_1, \ldots, x_d)$ where Q is a symmetric multilinear function with $Q(\mathbf{0}) \neq 0$. Let

$$F(\mathbf{x}) = \frac{1}{Q(\mathbf{x})} = \sum_{\mathbf{r} \in \mathbb{Z}^d} a_{\mathbf{r}} \mathbf{x}^{\mathbf{r}},$$

converging in some polydisk $\mathcal{D} \subset \mathbb{C}^d$. Often one focuses on the diagonal coefficients $\delta_n := a_{n,\ldots,n}$, whose univariate generating function $\mathsf{diag}_F(z) := \sum_n \delta_n z^n$ satisfies a linear differential equation with polynomial coefficients, but may be transcendental. A number of questions are natural, including nonnegativity (are all coefficients nonnegative), eventual nonnegativity (all but finitely many coefficients nonnegative), diagonal extraction (computing diag_F from Q), diagonal asymptotics, multivariate asymptotics and phase transitions in the asymptotics of $\{a_{\mathbf{r}}\}$.

The positivity (nonnegativity) question is the most classical, dating back at least to Szegő's work in [26]. The techniques, some of which are indicated in the next section, used in the literature are diverse and include integral methods and special functions, positivity preserving operators, combinatorial identities, computer algebra such as cylindrical algebraic decomposition, or determinantal methods. Contrasting to these methods are analytic combinatorial several-variable methods (ACSV) as developed in [20]. These are typically asymptotic, rather than exact, and therefore less useful for proving classical positivity statements, though they can be used to disprove them. Their chief advantages are their broad applicability and, increasingly, the level to which they have been automated. Our aim in this paper is to apply ACSV methods to a number of previously studied families of rational coefficient sequences, thereby extending what is known as well as illuminating the relative advantages of each method.

1.1 Previously studied instances

Let $\mathcal{M}_d$ denote the class of symmetric functions of d variables that are multilinear (degree 1 in each variable). This class of generating functions $F(\mathbf{x}) := 1/Q(\mathbf{x})$ where $Q \in \mathcal{M}_d$ includes a great number of previously studied cases, some of which we now review. Here and in the following, we use d for the number of variables and boldface $\mathbf{x}, \mathbf{y}, \mathbf{z}$, etc., for vectors of length d of integer, real or complex numbers. When d is small we use x, y, z, w for x_1, x_2, x_3, x_4. Let $e_k = e_{k,d}$ denote the k^{th} elementary symmetric function of d variables, the sum of all distinct k element products from the set of d variables. An equivalent description of the class $\mathcal{M}_d$ is that it contains all linear combinations of $\{e_{k,d} : 0 \leq k \leq d\}$.

The Askey-Gasper rational function is

$$A(x, y, z) := \frac{1}{1 - x - y - z + 4xyz}, \tag{1}$$

which, in the previous notation, is $A(\mathbf{x}) = F(\mathbf{x})$ when $d = 3$ and $Q = 1 - e_1 + 4e_3$. Gillis, Reznick and Zeilberger [11] deduce positivity of A from positivity of a 4-variate extension due to Koornwinder [15], for which they give a short elementary proof using a positivity preserving operation. Gillis, Reznick and Zeilberger also provide an elementary proof of the stronger result by Askey and Gasper [3] that A^β is positive for $\beta \geq (\sqrt{17}-3)/2 \approx 0.56$, by deriving a recurrence relation for the coefficients that makes positivity apparent.

Specific functions in $\mathcal{M}_4$ that have shown up in the literature include the Szegő rational function

$$S(x,y,z,w) := \frac{1}{e_3(1-x,1-y,1-z,1-w)} \tag{2}$$

as well as the Lewy-Askey function

$$L(x,y,z,w) := \frac{1}{e_2(1-x,1-y,1-z,1-w)}, \tag{3}$$

which is a rescaled version of $1/Q(\mathbf{x})$ with $d=4$ and $Q = 1 - e_1 + \frac{2}{3}e_2$. Szegő [26] proved that (2) is positive. In fact, he showed that $e_{d-1,d}^{-\beta}(1-\mathbf{x})$ is nonnegative if $\beta \geq 1/2$. His proof relates the power series coefficients to integrals of products of Bessel functions and, among other ingredients, employs the Gegenbauer–Sonine addition theorem. Scott and Sokal [22] establish a vast and powerful generalization of this result by showing that, if T_G is the spanning-tree polynomial of a connected series-parallel graph, then $T_G^{-\beta}(1-\mathbf{x})$ is nonnegative if $\beta \geq 1/2$. In the simplest non-trivial case, if G is a d-cycle, then $T_G = e_{d-1,d}$, thus recovering Szegő's result. Relaxing the condition on β, Scott and Sokal further extend their results to spanning-tree polynomials of general connected graphs. They do so by realizing that Kirchhoff's matrix-tree theorem implies that these polynomials can be expressed as determinants, and by proving that determinants of this kind are nonnegative. As another consequence of this determinantal nonnegativity, Scott and Sokal conclude that (3) is nonnegative, thus answering a question originating with Lewy [2] (with positivity replaced by nonnegativity). Kauers and Zeilberger [14] show that positivity of the Lewy-Askey rational function (3) would follow from positivity of the four variable function

$$K(x,y,z,w) := \frac{1}{1 - e_1 + 2e_3 + 4e_4}. \tag{4}$$

However, the conjectured positivity (or even nonnegativity) of (4) remains open.

As noted above, $e_{d-1,d}^{-\beta}(1-\mathbf{x})$ is nonnegative if $\beta \geq 1/2$. The asymptotics of $e_{k,d}^{-\beta}(1-\mathbf{x})$ are computed in [5] for $(k,d) = (2,3)$. In the cone $2(rs+rt+st) > r^2+s^2+t^2$, the coefficient $a_{r,s,t}$ is asymptotically positive when $\beta > 1/2 = (d-k)/2$ and not when $\beta < 1/2$. A conjecture of Scott and Sokal that remains open in both directions is that, for general k and d, the condition $\beta \geq (d-k)/2$ is necessary and sufficient for nonnegativity of the coefficients of $e_{k,d}^{-\beta}(1-\mathbf{x})$.

Gillis, Reznick and Zeilberger [11] consider the family

$$F_{c,d}(x_1,\ldots,x_d) := \frac{1}{1 - e_1 + c\,e_d} \tag{5}$$

of rational functions, where c is a real parameter. When $c < 0$, the coefficients are trivially positive, therefore it is usual to assume $c > 0$. Gillis, Reznick and Zeilberger show that $F_{c,3}$ has nonnegative coefficients if $c \leq 4$ (and this condition is shown to be necessary in [23]), but they conjecture that the threshold for $d \geq 4$ has a different form, namely that $F_{c,d}$ has nonnegative coefficients if and only if $c \leq d!$. It is claimed in [11], but the proof is omitted due to its length, that nonnegativity of $F_{d!,d}$ is implied by nonnegativity of the diagonal power series coefficients. In the cases $d = 4,5,6$, Kauers [13] proved nonnegativity of these diagonal coefficients by applying cylindrical algebraic decomposition (CAD) to the respective recurrences. On the other hand, it is suggested in [25] that the diagonal coefficients are eventually positive if $c < (d-1)^{d-1}$.

1.2 Previous questions and results on diagonals

The diagonal generating function diag_F and the sequence $\delta_n := a_{n,\ldots,n}$ it generates have received special attention. One reason is that the question of multivariate asymptotics in the diagonal direction is simply stated, whereas the question of asymptotics in all possible directions requires discussion of different possible phase regimes, a notion of uniformity over directions, degeneracies when the coordinates are not of comparable magnitudes, and so forth. Another reason is that there are effective methods for determining diag_F from Q, transferring the problem to the familiar univariate realm.

We briefly recall the theory of diagonal extraction. A d-variate power series F is said to be D-finite if the formal derivatives $\{\partial_{\mathbf{r}} F : \mathbf{r} \in (\mathbb{Z}^+)^d\}$ form a finite dimensional vector space over $\mathbb{C}[\mathbf{x}]$. In one variable, this is equivalent to F satisfying a linear differential equation with polynomial coefficients,

$$\sum_{i=0}^{k} q_i(z) \frac{d^i}{dz^i} F = 0, \quad q_i \in \mathbb{C}[z].$$

▶ **Proposition 1** (D-finite closure under diagonals [17]). *Let $F(\mathbf{x})$ be a D-finite power series. Then $\mathsf{diag}(z) := \sum_n \delta_n z^n$ is D-finite, where $\delta_n := a_{n,\ldots,n}$.*

When F is a rational function and $d = 2$, it was known that diag is algebraic (and thus D-finite) at least by the late 1960's [10, 12], and in special cases by Pólya in the 1920's [21]. In the rational function $F(x, y) = P(x, y)/Q(x, y)$ one substitutes $y = 1/x$ and computes a residue integral to extract the constant coefficient. The basis for Lipshitz' proof was the realization that the complex integration can be viewed as purely formal. With the advent of computer algebra this formal D-module computation was automated, with an early package in Macaulay and more widely used modern implementations in Magma, Mathematica and Maple. Due to advances in software and processor speed, these computations are often completable on functions arising in applications. Christol [8] was the first to show that diagonals of *rational* functions are D-finite.

The following relationship between D-finiteness of a univariate function and the existence of a polynomial recursion satisfied by its coefficient sequence is the result of translating a formal differential equation into a relation among the coefficients.

▶ **Proposition 2.** *The series $f(z) = \sum_{n\ge 0} a_n z^n$ is D-finite if and only if it is polynomially recursive, meaning that there is a $k > 0$ and there are polynomials $p_0, \ldots, p_k$, not all zero, such that for all but finitely many n,*

$$\sum_{i=0}^{k} p_i(n) f(n+i) = 0\,.$$

Let f be a D-finite power series in one variable. If f has positive finite radius of convergence and integer coefficients, then it is a so-called *G-function* and has well behaved asymptotics according to following result.

▶ **Proposition 3** (Asymptotics of G-Function Coefficients). *Suppose f is D-finite with finite radius of convergence and integer coefficients annihilated by a minimal order linear differential operator $\mathcal{L}$ with polynomial coefficients. Then $\mathcal{L}$ has only regular singular points in the Frobenius sense. Consequently, the coefficients $\{a_n\}$ are given asymptotically by a formula*

$$a_n \sim \sum_{\alpha} C_\alpha n^{\beta_\alpha} \rho_\alpha^{-n} (\log n)^{k_\alpha} \tag{6}$$

where the sum is over quadruples $(C_\alpha, b_\alpha, \rho_\alpha, k_\alpha)$ as α ranges over a finite set A with the following properties. The base ρ_α is an algebraic number, a root of the leading polynomial coefficient of $\mathcal{L}$. The β_α are rational and for each value of ρ_α can be determined as roots of an explicit polynomial constructed from ρ_α and $\mathcal{L}$. The log powers k_α are nonnegative integers, zero unless for fixed ρ_α there exist two values of β_α differing by an integer (including multiplicities in the construction of β_α). The C_α are not in general closed form analytic expressions, but may be determined rigorously to any desired accuracy.

Proof. The discussion in [18, page 37] gives references to several published results that together establish this proposition; see also Flajolet and Sedgewick [9, Section VII. 9]. Determination of all rational and algebraic numbers other than C_α is known to be effective. ◀

Because there are computational methods for the study of diagonals, it is of interest to reduce positivity questions to those involving only diagonals. For the Gillis-Reznick-Zeilberger class $F_{c,d}$, such a result is conjectured.

▶ **Conjecture 4** ([11]). *For $d \geq 4$, the following three statements are equivalent.*

(i) $c \leq d!$

(ii) *The diagonal coefficients of $F_{c,d}$ are nonnegative*

(iii) *All coefficients of $F_{c,d}$ are nonnegative*

To be precise, $(iii) \Rightarrow (ii) \Rightarrow (i)$ is trivial (look at δ_1); nonnegativity of all coefficients of $F_{c,d}$ holds for some interval $c \in [0, c_{\max}]$, therefore the conjecture comes down to nonnegativity of $F_{d!,d}$. A proof for $(ii) \Rightarrow (iii)$ in the case $c = d!$ is claimed in [11] but omitted from the paper due to length. This question is generalized in [25] to all of $\mathcal{M}_d$.

▶ **Question 5** ([25, Question 1.1 and following]). *For $Q \in \mathcal{M}_d$ and $F = 1/Q$, under what conditions does nonnegativity of the coefficients of diag_F imply nonnegativity of all coefficients of F?*

More specifically, with nonnegativity in place of positivity, the authors of that paper wonder whether positivity of F is equivalent to positivity of diag_F together with positivity of $F(x_1, \dots, x_{d-1}, 0)$. They prove that this is true for $d = 2$ and, with additional evidence, conjecture this to be true for $d = 3$ as well. Combined with [23, Conjecture 1] and [25, Conjecture 3.3], we obtain the following explicit predictions on the diagonal coefficients.

▶ **Conjecture 6.** *Let $F = 1/Q$ where $Q = 1 - e_1 + ae_2 + be_3$, which is, up to rescaling, the general element of $\mathcal{M}_3$. Then diag_F is nonnegative if and only if*

$$b \leq \begin{cases} 6(1-a) & a \leq a_0 \\ 2 - 3a + 2(1-a)^{3/2} & a_0 \leq a \leq 1 \\ -a^3 & a \geq 1, \end{cases} \tag{7}$$

where $a_0 \approx -1.81$ is characterized by $6(1-a_0) = 2 - 3a_0 + 2(1-a_0)^{3/2}$.

1.3 Present results

In the present work we use ACSV to answer asymptotic versions of these questions. Aside from computing special cases, the main new results are (1) simplification for diagonals with symmetric denominators via the Grace-Walsh-Szegő Theorem (Lemma 15 below); (2) an easy further simplification for the Gillis-Reznick-Zeilberger class (Lemma 18 below); and

(3) a topological computation to explain the drop in magnitude of coefficients at critical parameter values (Theorem 22 below).

The first special case we look at is the diagonal of the general element of $\mathcal{M}_3$, corresponding to Conjecture 6.

▶ **Theorem 7.** *Let $Q = 1 - e_1 + ae_2 + be_3$, let $F = 1/Q = \sum_{\mathbf{r}} a_{\mathbf{r}} \mathbf{z}^{\mathbf{r}}$ and let $\delta_n = a_{n,\dots,n}$ be the diagonal coefficients of F. Then δ_n is eventually positive when*

$$b < \begin{cases} -9a & a \le -3 \\ 2 - 3a + 2(1-a)^{3/2} & -3 \le a \le 1 \\ -a^3 & a \ge 1 \end{cases} \tag{8}$$

while, when the inequality is reversed, δ_n attains an infinite number of positive and negative values.

Theorem 7 is obtained by examining asymptotic regimes, captured in the following result.

▶ **Theorem 8.** *Let Q, F, and δ_n be as in Theorem 7. Assuming that b is not equal to the piecewise function in Equation (8),*

$$\delta_n = \sum_{x \in E} \left(\frac{x^{-3n}}{n} \cdot \left| \frac{1 - 2ax - bx^2}{1 - ax} \right| \cdot \frac{1}{2\sqrt{3}(1 - 2x + ax^2)} \right) \left(1 + O\left(\frac{1}{n}\right) \right), \tag{9}$$

where E consists of the minimal modulus roots of the polynomial $Q(x,x,x) = 1 - 3x + 3ax^2 + bx^3$.

The situation for eventual positivity on the diagonal when equality holds in Equation (8) is more delicate. When $a < -3$ it follows from seeing that there are two diagonal minimal points, (r,r,r) and $(-r,-r,-r)$, with a greater constant at the positive point. When $-3 < a < 1$, it follows from a dominant positive real cone point. When $a = -3$ a quadratically degenerate smooth point at $(-1/3, -1/3, -1/3)$ may be shown via rigorous numerical diagonal extraction to dominate the cone point at $(1/3, 1/3, 1/3)$, leading to alternation. When $a = 1$, $a_{\mathbf{r}} \equiv 1$. Finally, when $a > 1$, there are three smooth points on the unit circle, with nonnegativity conjectured because the positive real point is degenerate and should dominate.

Our second set of results concern the diagonal of the general element of the GRZ rational function $F_{c,d}$. Let

$$c_* = c_*(d) := (d-1)^{d-1}\,. \tag{10}$$

The following corresponds to Conjecture 4.

▶ **Theorem 9.** *Let $d \ge 4$. Then the diagonal coefficients of $F_{c,d}$ are eventually positive when $c < c_*$ and contain an infinite number of positive and negative values when $c > c_*$. When $c < c_*$, there is a conical neighborhood $\mathcal{N}$ of the diagonal such that $a_{\mathbf{r}} > 0$ for all but finitely many $\mathbf{r} \in \mathcal{N}$.*

Again, the result is obtained through an explicit asymptotic analysis.

▶ **Theorem 10.** *Let δ_n be the diagonal coefficients of $F_{c,d}$. Then when $c \ne c_*$,*

$$\delta_n = \sum_{x \in E} \left(\frac{x^{-dn}}{n^{(d-1)/2}} \cdot \left(\frac{2\pi(1-(d-1)r)}{r^{(d-1)/2}} \right)^{(d-1)/2} \cdot \frac{1}{d^{1/2}(1-(d-1)r)} \right) \left(1 + O\left(\frac{1}{n}\right) \right),$$

where E consists of the minimal modulus roots of the polynomial $1/F_{c,d}(x,\dots,x) = 1 - dx + cx^d$.

These theorems are proven in Section 4, using ACSV smooth point methods summarized in Section 2, however the case $c = c_*$ for the GRZ rational function requires the more delicate results of Section 5.

1.4 Exponential drop and further results

In the GRZ family, for even values of $d \geq 4$ the exponential growth rate of the coefficients drops at the special value $c = (d-1)^{d-1}$. This special value, and the corresponding drop in exponential growth, may be identified for each fixed d from the differential equation annihilating the diagonal. For example, when $d = 4$ an annihilating differential equation for the diagonal of $F_{c,4}$ is computed by D-module integration in the Mathematica package of Koutschan [16] producing the annihilating operator $\mathcal{L}$, of order 3 and maximum coefficient degree 8, such that $\mathcal{L}\mathsf{diag}_{F_{c,4}} = 0$:

$$\begin{aligned}\mathcal{L} = z^2&(c^4z^4 + 4c^3z^3 + 6c^2z^2 + 4cz - 256z + 1)(3cz-1)^2\partial_z^3\\ &+ 3z(3cz-1)(6c^5z^5 + 15c^4z^4 + 8c^3z^3 - 6c^2z^2 - 384cz^2 - 6cz + 384z - 1)\partial_z^2\\ &+ (cz+1)(63c^5z^5 - 3c^4z^4 - 66c^3z^3 + 18c^2z^2 + 720cz^2 + 19cz - 816z + 1)\partial_z\\ &+ 9c^6z^5 - 3c^5z^4 - 6c^4z^3 + 18c^3z^2 - 360c^2z^2 + 13c^2z - 384cz + c - 24. \end{aligned} \tag{11}$$

When $c = 27$, all coefficients in (11) acquire enough zeros at $z = 1/81$ that the quantity $(81z-1)^4$ may be factored out of the entire operator, leaving the following operator of order 3 and maximum degree 4:

$$\begin{aligned}\mathcal{L}_{27} :=& z^2(81z^2 + 14z + 1)\,\partial_z^3 + 3z(162z^2 + 21z + 1)\,\partial_z^2\\ &+ (21z+1)(27z+1)\partial_z + 3(27z+1). \end{aligned} \tag{12}$$

Asymptotics for δ_n may be extracted via the methodology described in Proposition 3. In the special case $d = 4, c = 27$, the recursion may be found on the OEIS (entry A125143) and identifies $\{\delta_n\}$ as the *Almkvist–Zudilin numbers*[5] from [1, sequence (4.12)(δ)]. The known asymptotic formula implies that $|\delta_n|^{1/n} \to 9$. However, as $c \neq 27$ approaches 27 from either side, we have

$$\lim_{c\to 27}\lim_{n\to\infty} |\delta_n|^{1/n} = 81;$$

in other words, the growth rate at $c = 27$ drops suddenly from 81 to 9. The occurrence of a phase change at $(d-1)^{d-1}$ for all d and drop in exponential rate for even $d \geq 4$ had not previously been proved. The special role of the case $c = (d-1)^{d-1}$ was observed in [25, Example 4.4] and claimed to agree with intuition from hypergeometric functions. We verify this, first by identifying the singularity from an ACSV point of view and then by checking that this singularity indeed produces the observed dimension drop.

▶ **Theorem 11** (exponential growth approaching criticality). *For all $d \geq 2$,*

$$\lim_{c\to c_*}\limsup_{n\to\infty} |\delta_n|^{1/(dn)} = d-1\,.$$

▶ **Theorem 12** (dimension drop at criticality). *When $c = c_*$ and $d \geq 4$ is even,*

$$\limsup_{n\to\infty} |\delta_n|^{1/(dn)} < d-1\,.$$

Theorem 12 is proved in Section 5.

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[5] That these are the diagonals of the rational function $F_{27,4}$ was observed in [24], where it is further conjectured that the coefficients of $F_{27,4}$ satisfy very strong congruences.

2 ACSV

In this section we describe the basic setup for ACSV and state some existing results. Definitions for the topological and geometric quantities used below can be found in Pemantle and Wilson [20]. Throughout this section let $F(\mathbf{z}) = P(\mathbf{z})/Q(\mathbf{z}) = \sum_{\mathbf{r}} a_{\mathbf{r}}\mathbf{z}^{\mathbf{r}}$ denote a rational series in d variables, with P and Q co-prime polynomials. Assume that F has a (finite) positive radius of convergence; that is, $Q(\mathbf{0}) \neq 0$ and P/Q is not a polynomial. Let $\mathcal{V} := \{\mathbf{z} \in \mathbb{C}^d : Q(\mathbf{z}) = 0\}$ denote the singular variety for F and let $\mathcal{M} = (\mathbb{C}^*)^d \setminus \mathcal{V}$ where $\mathbb{C}^* = \mathbb{C} \setminus \{0\}$. Coefficients $a_{\mathbf{r}}$ are extracted via the multivariate Cauchy formula

$$a_{\mathbf{r}} = \frac{1}{(2\pi i)^d} \int_{\mathbf{T}} \mathbf{z}^{-\mathbf{r}} F(\mathbf{z}) \frac{d\mathbf{z}}{\mathbf{z}}, \tag{13}$$

where $d\mathbf{z}/\mathbf{z}$ denotes the holomorphic logarithmic volume form $(dz_1/z_1) \wedge \cdots \wedge (dz_d/z_d)$ and $\mathbf{T}$ denotes a small torus (a product of sufficiently small circles about the origin in each coordinate, so that the product of the corresponding disks is disjoint from $\mathcal{V}$). The fundamental insight of ACSV is that the integral depends only on the homology class of $\mathbf{T}$ in $H_d(\mathcal{M})$. Therefore, one tries to replace $\mathbf{T}$ by some homologous chain $\mathcal{C}$ over which the integral is easier, typically via some combination of residue reductions and saddle point estimates.

A *direction* of asymptotics is an element $\hat{\mathbf{r}} \in (\mathbb{RP}^d)^+$; that is, a projective vector in the positive orthant. If $\mathbf{r} \in (\mathbb{R}^d)^+$ we write $\hat{\mathbf{r}}$ to denote the representative $\mathbf{r}/|\mathbf{r}|$ of the projective equivalence class containing $\mathbf{r}$, where $|\mathbf{r}| = |\mathbf{r}|_1 := r_1 + \cdots + r_d$. Given a Whitney stratification of $\mathcal{V}$ into smooth manifolds, the *critical set* $\mathsf{crit}(\hat{\mathbf{r}})$ for a direction $\hat{\mathbf{r}}$ is the set of $\mathbf{z} \in \mathcal{V}$ such that $\hat{\mathbf{r}}$ is orthogonal to the tangent space of the stratum of $\mathbf{z}$ in $\mathcal{V}$. If $\mathbf{z}$ is a smooth point of $\mathcal{V}$ and Q is square-free, this means $\hat{\mathbf{r}}$ should be parallel to the logarithmic gradient $(z_1\partial Q/\partial z_1, \ldots, z_d\partial Q/\partial z_d)$. A *minimal* point for direction $\hat{\mathbf{r}}$ is a point $\mathbf{z} \in \mathsf{crit}(\hat{\mathbf{r}})$ such that the open polydisk $\mathcal{D}(\mathbf{z}) := \{\mathbf{w} : |w_j| < |z_j| \, \forall 1 \leq j \leq d\}$ does not intersect $\mathcal{V}$. The minimal point $\mathbf{z}$ is called *strictly minimal* if the closed polydisk $\overline{\mathcal{D}(\mathbf{z})}$ intersects $\mathcal{V}$ only at $\mathbf{z}$.

For any $\boldsymbol{\beta} \in \mathbb{R}^d$, let $\mathbf{T}(\boldsymbol{\beta}) = \{\mathbf{w} : |w_j| = \exp(\beta_j) \, \forall 1 \leq j \leq d\}$ denote the torus of points with log modulus vector $\boldsymbol{\beta}$. The *amoeba* of $Q(\mathbf{z})$ is the image of $\mathcal{V}$ under the map $\mathrm{Relog}(\mathbf{z}) = (\log|z_1|, \ldots, \log|z_d|)$, while the *height* of a point $\mathbf{z}$ is $h_{\hat{\mathbf{r}}}(\mathbf{z}) = -\hat{\mathbf{r}} \cdot \mathrm{Relog}(\mathbf{z})$. Except in Section 5, all ACSV computations are based on the following result.

▶ **Theorem 13** (smooth point formula). *Fix $F = P/Q = \sum_{\mathbf{r}} a_{\mathbf{r}}\mathbf{z}^{\mathbf{r}}$ and vector $\mathbf{r} \in (\mathbb{R}^d)^+$ in direction $\hat{\mathbf{r}}$. Assume there exists $\boldsymbol{\beta} \in \mathbb{R}^d$ such that the following two hypotheses hold.*

1 **Finite critical points on the torus.** *The set $E := \mathbf{T}(\boldsymbol{\beta}) \cap \mathsf{crit}(\hat{\mathbf{r}})$ is finite, nonempty and contains only minimal smooth points.*

2 **Quadratic nondegeneracy**. *At each $\mathbf{z} \in E$ fix $k = k(\mathbf{z})$ such $\partial Q/\partial z_k(\mathbf{z}) \neq 0$ and let $z_k = g(z_1, \ldots, \hat{z_k}, \ldots, z_d)$ be a smooth local parametrization of z_k on $\mathcal{V}$ as a function of $\{z_j : j \neq k\}$. We assume that the Hessian determinant $\mathcal{H}_{k(\mathbf{z})}$ of second partial derivatives of $g\left(w_1 e^{i\theta_1}, \ldots, w_d e^{i\theta_d}\right)$ with respect to the θ_j at the origin is non-zero for each $\mathbf{z} \in E$.*

Then there exists a closed neighborhood $\mathcal{N}$ of $\hat{\mathbf{r}}$ in $(\mathbb{R}^d)^+$ on which all the above hypotheses hold and, for any $\mathbf{r}$ with $\hat{\mathbf{r}}$ in this neighborhood,

$$a_{\mathbf{r}} = (2\pi)^{(1-d)/2} \sum_{\mathbf{z} \in E} \det \mathcal{H}_{k(\mathbf{z})}^{-1/2} \frac{P(\mathbf{z})}{z_k(\partial Q/\partial z_k)(\mathbf{z})} r_k^{(1-d)/2} \mathbf{z}^{-\mathbf{r}} + O\left(r_k^{-d/2}\mathbf{z}^{-\mathbf{r}}\right). \tag{14}$$

▶ **Remark.** *A number of other formulae for $a_{\mathbf{r}}$ are equivalent to this one and hold under the same hypotheses. An explicit formula for $\mathcal{H}_k$ in terms of partial derivatives of Q is given* *in [18, Theorem 54]. The following coordinate-free formula for the constants involved in terms of the complexified Gaussian curvature $\mathcal{K}$ at a smooth point $\mathbf{z} \in \mathcal{V}$ is given in [20, (9.5.2)] as*

$$a_{\mathbf{r}} = (2\pi)^{(1-d)/2} \left[\sum_{\mathbf{z}\in E} \mathcal{K}(\mathbf{z})^{-1/2} \, |\nabla_{\log} Q(\mathbf{z})|^{-1} P(\mathbf{z}) \, |\mathbf{r}|^{(1-d)/2} \, \mathbf{z}^{-\mathbf{r}} \right] + O\left(|\mathbf{r}|^{-d/2} |\mathbf{z}|^{-\mathbf{r}} \right) \quad (15)$$

Proof. Assume first that $\log|\mathbf{w}|$ is the unique minimizer of $\mathbf{r} \cdot \mathbf{x}$ on the boundary of the log domain of convergence (this being a component of the complement of the amoeba). Under no assumptions on E or $\mathcal{K}$, Theorem 9.3.2 of [20] writes the multivariate Cauchy integral 13 as the integral of a residue form ω over an intersection cycle, $\mathcal{C}$. Taking into account that E is finite, and assuming an extra hypothesis that $\mathbf{r}$ is a *proper direction* (see [5, Definition 2.3]), Theorem 9.4.2 of [20] identifies $\mathcal{C}$ as a sum of quasi-local cycles near the points of E. For each such $\mathbf{z}$, if $\partial Q/\partial z_k$ and $\det \mathcal{H}_k$ do not vanish, Theorem 9.2.7 of [20] identifies the integral as the corresponding summand in (14). Nonvanishing of $\mathcal{H}_k$ is equivalent to nonvanishing of $\mathcal{K}$, leading to the coordinate-free formula (15), which may be found in [20, Theorem 9.3.7]. This proves the theorem under an extra hypothesis on the amoeba boundary.

To remove the properness hypothesis, consider the intersection cycle $\mathcal{C}$ obtained from expanding the torus $\mathbf{T}(\boldsymbol{\beta} - \epsilon\mathbf{r})$ inside the domain of convergence of F to a torus $\mathbf{T}(\boldsymbol{\beta} + \epsilon\mathbf{r})$. The construction in [20, Section A4] gives a compact $(d-1)$-chain representing a relative cycle in $H_{d-1}(\mathcal{V}^{c+\varepsilon}, \mathcal{V}^{c-\varepsilon})$; that is, a chain of maximum height $c+\varepsilon$ with maximum boundary height $c - \varepsilon$. Applying the downward gradient flow of $h_{\hat{\mathbf{r}}}$ on $\mathcal{V}$ for arbitrarily small time, we arrive again at a chain satisfying the conclusions of [20, Theorem 9.4.2]. Because the deformed chain has nonvanishing boundary, one must add a term for the chain swept out by the deformation applied to this boundary, but the elements of this chain have height at most $c - \varepsilon$ so the resulting integral will grow within the error term above. ◀

▶ **Corollary 14.** *Assume the hypotheses of Theorem 13, and fix a vector $\mathbf{v}$ in direction $\hat{\mathbf{r}}$.*

(i) *If $E = \{\mathbf{z}\}$ for some $\mathbf{z}$ in the positive real orthant in $\mathbb{C}^d$ and the leading constant of Equation (14) is positive, then there exists a neighbourhood of $\hat{\mathbf{r}}$ such that all but finitely many coefficients $\{a_{\mathbf{r}} : \hat{\mathbf{r}} \in \mathcal{N}\}$ are positive.*

(ii) *If $E = \{\mathbf{z}\}$ for some $\mathbf{z}$ such that $\mathbf{z}^{\mathbf{v}} := \prod_{j=1}^{d} z_j^{v_j}$ is positive real and the leading constant of Equation (14) is positive, then all but finitely many coefficients $a_{n\mathbf{v}}$ are positive.*

(iii) *If E does not contain a point $\mathbf{z}$ with $\mathbf{z}^{\mathbf{v}}$ positive real and the sum in Equation (14) is not identically zero, then infinitely many coefficients $a_{n\mathbf{v}}$ are positive and infinitely many $a_{n\mathbf{v}}$ are negative.*

▶ **Remark.** *When E contains a point in the positive real orthant but it is not a singleton, the corollary does not provide information as to eventual positivity.*

Proof. Conclusions (i) and (ii) follow immediately from (14) because the sum is a single positive term.

For conclusion (iii), grouping the elements of E by conjugate pairs we note that up to scaling by $\mathbf{z}^{n\mathbf{v}} n^{d/2}$ the asymptotic leading term of $a_{n\mathbf{v}}$ has the form

$$l_n = \sum_{i=1}^{|E|} a_i \cos(2\pi\theta_i n + \beta_i),$$

where each θ_i, a_i, β_i is real, and $\theta_i \in (0,1)$. If r_n is any sequence satisfying a linear recurrence relation with constant coefficients, and $r_n = O(1/n)$, then Bell and Gerhold [6, Section 3] show that $l_n > r_n$ infinitely often. Since the modulus of the error term in Equation (14) can be bounded by a linear recurrence sequence with growth $O(1/n)$, we see that $a_{n\mathbf{v}}$ is positive infinitely often. Repeating the argument with $-l_n$ shows that $a_{n\mathbf{v}}$ is negative infinitely often. ◀

Any computer algebra system can compute the set of smooth critical points in $\mathsf{crit}(\hat{\mathbf{r}})$ by solving the $d-1$ equations $(\nabla_{\log} Q)(\mathbf{z}) \parallel \hat{\mathbf{r}}$ together with the equation $Q(\mathbf{z}) = 0$, where $\nabla_{\log} Q = (z_1 \partial Q/\partial z_1, \ldots, z_d \partial Q/\partial z_d)$. Identifying which points in crit are minimal is more difficult, although still effective [19]. For our cases, we can use results about symmetric functions to help with the computations. For any polynomial Q in d variables, let δ^Q denote the codiagonal: the univariate polynomial defined by $\delta^Q(x) = Q(x, \ldots, x)$.

▶ **Lemma 15** (polynomials in $\mathcal{M}_d$ have diagonal minimal points)**.** *Let $F = 1/Q$ with $Q \in \mathcal{M}_d$. Let x be a zero of δ^Q of minimal modulus. Then $\mathbf{x} := (x, \ldots, x)$ is a minimal point for F in crit$(1, \ldots, 1)$.*

This follows directly from the classical Grace-Walsh-Szegő Theorem, of which we now sketch a modern proof.

Proof. Let $\alpha_1, \ldots, \alpha_k$ be the roots of δ^Q, where $k \le d$ is the common degree of Q and δ^Q and $|\alpha_1|$ is minimal among $\{|\alpha_j| : j \le k\}$. For any $\varepsilon > 0$, the polynomial

$$M(\mathbf{x}) := \prod_{j=1}^{k} (x_j - \alpha_j)$$

has no zeros in the polydisk $\mathcal{D}$ centered at the origin whose radii are $\alpha_1 - \varepsilon$. The symmetrization of M (see [7]) is defined to be the multilinear symmetric function m such that $m(x, \ldots, x) = M(x, \ldots, x)$. In our case $M(x, \ldots, x) = \delta^Q(x)$, and it immediately follows that $m = Q$. By the Borcea-Brändén symmetrization lemma (see [7, Theorem 2.1]), the polynomial Q has no zeros in the polydisk $\mathcal{D}$. We conclude that the zero $\mathbf{x}$ of Q is a minimal point of F. ◀

3 Symmetric multilinear functions of three variables

In this section we determine the diagonal asymptotics for general $Q = 1 - e_1 + ae_2 + be_3 \in \mathcal{M}_3$. Taking the coefficient of e_1 to be 1 loses no generality because of the rescaling $x_j \to \lambda x_j$ which preserves $\mathcal{M}_d$ and affects coefficient asymptotics in a trivial way. In order to use Theorem 13, we begin by identifying minimal points. Lemma 15 dictates that our search should be on the diagonal.

To that end, let $\delta^Q(x) = Q(x, x, x) = 1 - 3x + 3ax^2 + bx^3$. The discriminant of δ^Q is a positive real multiple of $p(a, b) := 4a^3 - 3a^2 + 6ab + b^2 - 4b = (a - 1 + 3(b-1))^2 - 4(b-1)^3$, and the zero set of δ^Q is obtained from that of the cubic $4b^3 = -a^2$ by centering at $(1, -1)$ and shearing via $(a, b) \mapsto (a + 3b, b)$. The discriminant $p(a, b)$ vanishes along the red curve (solid and dashed) in Figure 1. Let $r_1(a)$ and $r_2(a)$ denote respectively the upper and lower branches of the solution to $p(a, b) = 0$.

▶ **Lemma 16.** *Let p be a minimal modulus root of δ^Q. Then any critical point of $1/Q$ on the torus $T(p, p, p)$ has the form (q, q, q) where $\delta^Q(q) = 0$.*

Proof. Gröbner basis computations show nondiagonal critical points to be permutations of $\left(\frac{1}{a}, \frac{1}{a}, \frac{a(1-a)}{a^2+b}\right)$, occurring when $b = a^2(a-2)$. When $a \le 1$, the only time the positive root

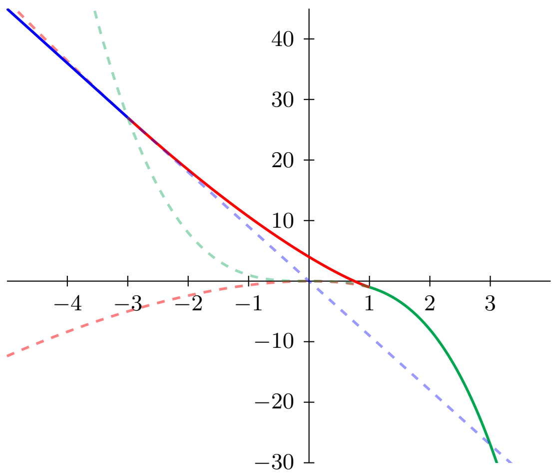

Figure 1 The three regimes defined by Proposition 17, made up of the curves $b = -9a$, $p(a, b) = 0$, and $b = -a^3$. Dashed lines represent the curves where they do not determine positivity of coefficients; note smoothness in the transitions between regimes.

of $\delta^Q(x)$ has modulus $1/|a|$ is the trivial case $(a, b) = (1, -1)$. When $b = a^2(a-2)$ and $a > 1$, the modulus of the product of the roots of $\delta^Q(x)$ equals $\frac{1}{a^2(a-2)}$ and the minimal roots of $\delta^Q(x)$ are a pair of complex conjugates. If this pair has modulus $1/a$, then the real root of $\delta^Q(x)$ is $\pm\frac{1}{a^4(a-2)}$, but $\delta^Q\left(\pm\frac{1}{a^4(a-2)}\right) \neq 0$ for $a > 1$. ◀

Determining asymptotics is thus a matter of determining the minimal modulus roots of $\delta^Q(x)$. The following may be proved by comparing moduli of roots, separating cases according to the sign of $p(a, b)$.

▶ **Proposition 17.** *The function δ^Q has a minimal positive real zero if and only if*

$$b \leq \begin{cases} -9a & a \leq -3 \\ r_1(a) & -3 \leq a \leq 1 \\ -a^3 & a \geq 1 \end{cases}$$

This corresponds to the set of points lying on and below the solid curve in Figure 1.

Proof of Theorems 7 and 8: Suppose b is greater than the piecewise expression in the proposition; then δ^Q has no minimal positive zero, so the product of the three coordinates of the minimal points determined above do not lie in the positive orthant. By part (iii) of Corollary 14, the diagonal coefficients are not eventually positive. Asymptotics of δ_n are determined by Theorem 13, and when b is less than the piecewise expression it can be verified that the dominant term is positive. ◀

4 The Gillis-Reznick-Zeilberger classes

Throughout this section, let $F = F_{c,d} = 1/Q_{c,d} = 1/(1 - e_1 + ce_d)$ and recall that $c_* = (d-1)^{d-1}$. Lemma 15 implies that for $Q \in \mathcal{M}_d$, in the diagonal direction, one may find diagonal minimal points. For $F_{c,d}$, things are even simpler: all critical points for diagonal asymptotics are diagonal points.

▶ **Lemma 18.** *Let $F_{c,d} = 1/Q_{c,d}$. If $\mathbf{z} \in \mathit{crit}(1, \ldots, 1)$ then $z_i = z_j$ for all $1 \leq i, j \leq d$.*

Proof. From $Q = Q_{c,d} = 1 - e_1 + ce_d$ we see that $(\nabla_{\log} Q)_j = -z_j - ce_d$ and hence that $(\nabla_{\log} Q)_i = (\nabla_{\log} Q)_j$ if and only if $z_i = z_j$. ◀

▶ **Proposition 19** (Smoothness of $F_{c,d}$ for $c \neq c_*$)**.** *Let $F_{c,d} = 1/Q_{c,d}$. If $c \neq c_*$ then $\mathcal{V}$ is smooth. If $c = c_*$ then $\mathcal{V}$ fails to be smooth at the single point $\mathbf{z}_* = (1/(d-1), \dots, 1/(d-1))$. When $c = c_*$, the singularity at $\mathbf{z}_*$ has tangent cone e_2.*

Proof. Checking smoothness of $\mathcal{V}$ we observe that for d fixed and c and $x_1, \dots, x_d$ variable, vanishing of the gradient of $Q_{c,d}$ with respect to the x variables implies $x_j = ce_d$ for all j. This common value, x, cannot be zero, hence $x_j \equiv x$ and $c = x^{1-d}$. Vanishing of $Q_{c,d}$ then implies vanishing of $1 - dx + x$, hence $x = 1/(d-1)$ and $c = c_*$. This proves the first two statements. Setting $c = c_*$ and $x_j = 1/(d-1) + y_j$ centers $Q_{c_*,d}$ at the singularity and produces a leading term of $(d-1)e_2(\mathbf{y})$, proving the third statement. ◀

4.1 Proof of Theorems 9 and 10 in the case $c < c_*$

When $c \leq 0$, the denominator of $F_{c,d}$ is one minus the sum of positive monomials, which leaves no doubt as to positivity. Assume, therefore, that $0 < c < c_*$. Apply Lemma 15 to see that if x is a minimum modulus zero of $\delta^Q := Q_{c,d}(x, \dots, x)$ then $(x, \dots, x)$ is a minimal point for $F_{c,d}$ in the diagonal direction. Apply Lemma 18 to conclude that the set E in Theorem 13 of minimal critical points on $\mathbf{T}(|x|, \dots, |x|)$ consists only of points $(y, \dots, y)$ such that y is a root of δ^Q. By part (i) of Corollary 14, it suffices to check that $\delta^Q = 1 - dx + cx^d$ has a unique minimal modulus root ρ and that $\rho \in \mathbb{R}^+$. Thus, the conclusion follows from the following proposition.

▶ **Proposition 20.** *For $c \in (0, c_*)$, the polynomial $\delta^Q = 1 - dx + cx^d$ has a root $\rho \in \left[\frac{1}{d}, \frac{1}{d-1}\right]$ which is the unique root of δ^Q of modulus less than $1/(d-1)$.*

Proof. Checking signs we find that $\delta^Q(1/d) = cd^{-d} > 0$ while $\delta^Q(1/(d-1)) = -(d-1)^{-1} + c(d-1)^{-d} < -(d-1)^{-1} + c_*(d-1)^{-d} = 0$, therefore there is at least one root, call it ρ, of δ^Q in the interval $[1/d, 1/(d-1)]$. On the other hand, when $|z| = 1/(d-1)$, we see that $|dz| \geq |1 + cz^d|$ and therefore, by applying Rouché's theorem to the functions $-dz$ and $1 + cz^d$, we see that δ^Q has as many zeros on $|z| < 1/(d-1)$ as does $-dz$: precisely one root, ρ. ◀

4.2 Proof of Theorems 9 and 10 in the case $c > c_*$

Again, by Lemmas 15 and 18, we may apply part (iii) of Corollary 14 to the set E of points $(y, \dots, y)$ for all minimal modulus roots y of δ^Q. The result then reduces to the following proposition.

▶ **Proposition 21.** *For $c > c_*$, the set of minimal modulus roots of the polynomial $\delta^Q = 1 - dx + cx^d$ contains no point whose d^{th} power is real and positive.*

Proof. First, if z^d is real then the imaginary part of $\delta^Q(z)$ is equal to the imaginary part of $-dz$, hence any root z of δ^Q with z^d real is itself real.

Next we check that δ^Q has no positive real roots. Differentiating $\delta^Q(x)$ with respect to x gives the increasing function $d(-1 + cx^{d-1})$ with a unique zero at $c^{-1/(d-1)}$. This gives the location of the minimum of δ^Q on $\mathbb{R}^+$, where the function value is $1 - dc^{-1/(d-1)} + c^{1-d/(d-1)} = 1 - (d-1)/c^{1/(d-1)}$ which is positive because $c > (d-1)^{d-1}$.

If d is even, δ^Q clearly has no negative real roots, hence no real roots at all, finishing the proof in this case. If d is odd δ^Q will have a negative real root u, however because d is odd, the product of the coordinates of $(u, \dots, u)$ is $u^d < 0$. ◀

We conjecture that the roots of minimal modulus when $c > c_*$ are always a complex conjugate pair, however this determination does not affect our positivity results.

4.3 Proof of Theorem 11

When $c < c_*$ we have seen that there is a single real minimal point $(\rho_c, \ldots, \rho_c)$ in the diagonal direction and that $\rho_c \uparrow 1/(d-1)$ as $c \uparrow c_*^-$. The limit from below in Theorem 11 then follows directly from Theorem 10.

For the limit from above, it suffices to show that in the diagonal direction, for c sufficiently close to c_* and greater, E consists of a single diagonal complex conjugate pair $(\zeta_c, \ldots, \zeta_c)$ and $(\overline{\zeta_c}, \ldots, \overline{\zeta_c})$, and that $\overline{\zeta_c} \to 1/(d-1)$ as $c_* \downarrow c$. First, we check that at $c = c_*$ the unique minimum modulus root of δ^Q is the doubled root at $1/(d-1)$. For $c = c_*$, the first and third terms of $\delta^Q = 1 - dz + c_* z^d$ have modulus 1 and $1/(d-1)$ when $|z| = 1/(d-1)$, respectively, summing to the modulus of the middle term; therefore if $\delta^Q(z) = 0$ and $|z| = 1/(d-1)$ then the third term is positive real. But then the second term must be positive real too, hence the unique solution of modulus at most $1/(d-1)$ is $z = 1/(d-1)$. A quick computation shows the multiplicity to be precisely 2. We know that for $c > c_*$ there are no real roots. Therefore, as c increases from c_*, the minimum modulus doubled root splits into two conjugate roots, which, in a neighborhood of c_*, are still the only minimum modulus roots.

5 Lacuna computations

The following theorem is the subject of forthcoming work [4]. Theorem 12 follows immediately from Theorem 22 below, with the following specifications: $d \geq 4$ and even, $c = c_*$, $k = 1$, $P = 1$, $Q = Q_{c,d}$, $\mathbf{z}_* = (1/d, \ldots, 1/d)$, $\hat{\mathbf{r}} = (1, \ldots, 1)$, B is the component of the complement of the amoeba of Q containing $(a, \ldots, a)$ for $a < -\log d$, $\mathbf{x}_* = (-\log d, \ldots, -\log d)$, $\mathbf{y}_* = \mathbf{0}$ and $\mathcal{N}$ taken to be the diagonal. Proposition 19 guarantees the correct shape for the tangent cone to Q at $\mathbf{z}_*$.

▶ **Theorem 22.** *Suppose $F = P/Q^k$ with P a holomorphic function and Q a real Laurent polynomial. Fix $\hat{\mathbf{r}} \in \mathbb{RP}^d$, let B be a component of the complement of the amoeba of Q, let $\sum_{\mathbf{r}} a_{\mathbf{r}} \mathbf{z}^{\mathbf{r}}$ be the Laurent expansion for F convergent for $\mathbf{z} = \exp(\mathbf{x} + i\mathbf{y})$ and $\mathbf{x} \in B$. Let $\mathbf{x}_* \in \partial B$ be the a maximizing point for $\mathbf{r} \cdot \mathbf{x}$ on ∂B. Assume that $\mathcal{V}$ has a unique singularity $\mathbf{z}_* = \exp(\mathbf{x}_* + i\mathbf{y}_*)$, and that the tangent cone of Q at $\mathbf{z}$ transforms by a real linear map to $z_d^2 - \sum_{j=1}^{d-1} z_j^2$. Let $\mathcal{N}$ be any closed cone such that $\mathbf{x}_*$ maximizes $\mathbf{r} \cdot \mathbf{x}$ for all $\mathbf{r} \in \mathcal{N}$.*

If $d > 2k$ is even then there is an $\varepsilon > 0$ and a chain Γ contained in the set $\mathcal{V}_\varepsilon := \{\mathbf{z} \in \mathcal{V} : |\mathbf{z}^{-\mathbf{r}}| \leq \exp(-\mathbf{r} \cdot \mathbf{x}_* - \varepsilon|\mathbf{r}|)$ such that

$$a_{\mathbf{r}} = \int_\Gamma \mathbf{z}^{-\mathbf{r}} \frac{P}{Q^k} \frac{d\mathbf{z}}{\mathbf{z}} \,. \tag{16}$$

In other words, the chain of integration can be slipped below the height of the singular point.

Sketch of proof: Expand the torus $\mathbf{T}$ of integration to $\mathbf{z}_*$ and just beyond. The integral (13) turns into a residue integral over an intersection cycle swept out by the expanding torus; see, e.g. [20, Appendix A.4]. For small perturbations Q_ε of Q, the residue cycle is the union of a sphere surrounding $\mathbf{z}_*$ and a hyperboloid intersecting the sphere. As $Q_\varepsilon \to Q$, this cycle may be deformed so that the sphere shrinks to a point while the hyperboloid's neck also constricts to a point. The hyperboloid may then be folded back on itself so that in a neighborhood of $\mathbf{z}_*$, the chain vanishes, leaving a chain Γ supported below the height of $\mathbf{z}_*$. ◀

A Appendix A: Maple Code

Maple worksheets going through the calculations discussed above can be found at `https://github.com/smelczer/SymmetricRationalFunctionsAofA` ; we include the main component of those worksheets, code giving dominant smooth asymptotics, here for archival purposes.

```
smoothASM := proc(G, H, vars, pt)
    local N, i, j, M, HES, C, U, lambda, sbs:
    N := nops(vars) :
    # Get the Hessian determinant of the phase implicitly
    for i from 1 to N do for j from 1 to N do
        U[i, j] := vars[i] · vars[j] · diff(Q, vars[i], vars[j]) :
    od: od:
    lambda := x · diff(Q, x) :
    for i from 1 to N − 1 do for j from 1 to N − 1 do
        if i <> j then M[i, j] := 1 + 1/lambda · (U[i, j] − U[i, N] − U[j, N] + U[N, N]) :
        else M[i, j] := 2 + 1/lambda · (U[i, i] − 2 · U[i, N] + U[N, N]) :
      fi:
    od: od:
    HES := LinearAlgebra[Determinant](Matrix([seq([seq(M[i, j], i = 1..N − 1)], j = 1..N − 1)])) :
    C := simplify(−G/vars[−1]/diff(H, vars[−1]) · HES^(−1/2) · (2 · Pi)^((1 − N)/2));
    sbs := seq(vars[j] = pt[j], j = 1..N) :
    return eval(1/mul(j, j = pt))^n · n^((1 − N)/2) · eval(subs(sbs, C)) :
end:
```

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