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Global residues for sparse polynomial systems

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1. Introduction

Let \( f_1 = \cdots = f_n = 0 \) be a system of Laurent polynomial equations in \( n \) variables whose Newton polytopes are \( \Delta_1, \ldots, \Delta_n \). Suppose the solution set \( Z_f \) in the algebraic torus \( \mathbb{T}^n = (\mathbb{C} - \{0\})^n \) is finite. This will be true if the coefficients of the \( f_i \) are generic.

The global residue assigns to every polynomial \( g \) the sum over \( Z_f \) of Grothendieck residues of the meromorphic form

\[
\omega_g = \frac{g}{f_1 \cdots f_n} \frac{dt_1}{t_1} \wedge \cdots \wedge \frac{dt_n}{t_n}.
\]

It is a symmetric function of the solutions and hence depends rationally on the coefficients of the system. Global residues were studied by Tsikh, Gelfond and Khovanskii, and later by Cattani, Dickenstein and Sturmfels [16,9,3,4]. There are numerous applications of global residues ranging from elimination algorithms in commutative algebra [4] to integral representation formulae in complex analysis [16].

There have been several approaches to the problem of computing the global residue explicitly. Gelfond and Khovanskii considered systems with generically positioned Newton polytopes. The latter means that for any linear function \( \xi \), among the corresponding extremal faces \( \Delta_1^\xi, \ldots, \Delta_n^\xi \) at least one is a vertex. In this case Gelfond and Khovanskii found an explicit formula for the global residue as a Laurent polynomial in the coefficients of the
system [9]. In general, the global residue is not a Laurent polynomial and one should not expect a closed formula for it.

Another approach was taken by Cattani and Dickenstein in the generalized unmixed case when all \( \Delta_i \) are dilates of a single \( n \)-dimensional polytope (see [3]). Their algorithm requires computing a certain element in the homogeneous coordinate ring of a toric variety whose toric residue equals 1. Then the Codimension Theorem for toric varieties [6] allows global residue computation using Gröbner bases techniques. This approach was then extended by D’Andrea and Khetan to a slightly more general ample case [7]. However, it turned out to be a hard (and still open) problem to find an element of toric residue 1 for an arbitrary collection of polytopes.\(^1\)

In this paper we present a new algorithm for computing the global residue when \( \Delta_1, \ldots, \Delta_n \) are arbitrary \( n \)-dimensional polytopes (see Section 5). The proof of its correctness is in the spirit of Cattani and Dickenstein’s arguments, but avoids the toric residue problem. It relies substantially on the Toric Euler–Jacobi theorem due to Khovanskii [13]. Also in our algorithm we replace Gröbner bases computations with solving a linear system. This gives an expression of the global residue as a quotient of two determinants. The same idea was previously used by D’Andrea and Khetan in [7].

There is an intimate relation between the global residue and polynomial interpolation. In the classical case this was understood already by Kronecker. In Section 3 we show how the Toric Euler–Jacobi theorem gives sparse polynomial interpolation. Another consequence of this theorem is a lower bound on the number of interior lattice points in the Minkowski sum of \( n \) full-dimensional lattice polytopes in \( \mathbb{R}^n \) (Corollary 3.2). Finally, our results give rise to interesting optimization problems about Minkowski sums which we discuss in Section 6.

2. Global residues in \( \mathbb{C}^n \) and Kronecker interpolation

We begin with classical results on polynomial interpolation that show how global residues come into play.

Let \( f_1, \ldots, f_n \in \mathbb{C}[t_1, \ldots, t_n] \) be polynomials of degrees \( d_1, \ldots, d_n \), respectively. Let \( \rho = \sum d_i - n \) denote the critical degree for the \( f_i \). We assume that the solution set \( Z_f \subset \mathbb{C}^n \) of \( f_1 = \cdots = f_n = 0 \) consists of a finite number of simple roots. The following is a classical problem on polynomial interpolation.

**Problem 1.** Given \( \phi : Z_f \to \mathbb{C} \) find a polynomial \( g \in \mathbb{C}[t_1, \ldots, t_n] \) of degree at most \( \rho \) such that \( g(a) = \phi(a) \) for all \( a \in Z_f \).

Kronecker [14] suggested the following solution to this problem. Since each \( f_i \) vanishes at every \( a \in Z_f \) we can write (non-uniquely):

\[
f_i = \sum_{j=1}^{n} g_{ij} (t_j - a_j), \quad a = (a_1, \ldots, a_n), \quad g_{ij} \in \mathbb{C}[t_1, \ldots, t_n].
\]

The determinant \( g_a \) of the polynomial matrix \( [g_{ij}] \) is a polynomial of degree at most \( \rho \). Notice that the value of \( g_a \) at \( t = a \) equals the value of the Jacobian \( J_f = \det \left( \frac{\partial f_i}{\partial t_j} \right) \) at \( t = a \), since \( \frac{\partial f_i}{\partial t_j} (a) = g_{ij}(a) \) from (2.1). Also \( g_a(a') = 0 \) for any \( a' \in Z_f, a' \neq a \). Indeed, substituting \( t = a' \) into (2.1) we get

\[
0 = \sum_{j=1}^{n} g_{ij}(a')(a'_j - a_j),
\]

which means that the non-zero vector \( a' - a \) is in the kernel of the matrix \( [g_{ij}(a')] \), and hence \( \det [g_{ij}(a')] = 0 \). It remains to put

\[
g = \sum_{a \in Z_f} \frac{\phi(a)}{J_f(a)} g_a.
\]

\(^1\) For a combinatorial construction of such an element that provides a solution to the problem for a wide class of polytopes see [10].
Remark 2.1. When choosing $g_{ij}$ in (2.1) one can assume that
\[ g_{ij} = \frac{\partial F_i}{\partial t_j} + \text{lower degree terms}, \]
where $F_i$ is the main homogeneous part of $f_i$. Then (2.2) becomes
\[ g = \left( \sum_{a \in Z_f} \frac{\phi(a)}{J_f(a)} \right) J_F + \text{lower degree terms}. \quad (2.3) \]
where $J_F$ is the Jacobian of the $F_i$.

Definition 2.2. Given $g \in \mathbb{C}[t_1, \ldots, t_n]$ the sum of the local Grothendieck residues
\[ R_f(g) = \sum_{a \in Z_f} \text{res}_a \left( \frac{g}{f_1 \cdots f_n} dt_1 \wedge \cdots \wedge dt_n \right) \]
is called the global residue of $g$ for the system $f_1 = \cdots = f_n = 0$. In the case of simple roots of the system we get
\[ R_f(g) = \sum_{a \in Z_f} \frac{g(a)}{J_f(a)}. \]

Theorem 2.3 (The Euler–Jacobi Theorem). Let $f_1 = \cdots = f_n = 0$ be a generic polynomial system with $\deg(f_i) = d_i$. Then for any $h$ of degree less than $\rho = \sum d_i - n$ the global residue $R_f(h)$ is zero.

Proof. Consider the function $h : Z_f \to \mathbb{C}, a \mapsto h(a)$. According to the previous discussion there is a polynomial of the form (2.3) which takes the same values on $Z_f$ as $h$. In other words,
\[ h \equiv \left( \sum_{a \in Z_f} \frac{h(a)}{J_f(a)} \right) J_F + \text{lower degree terms} \quad (\text{mod } I), \]
where we used that the ideal $I = (f_1, \ldots, f_n)$ is radical and the roots are simple. Comparing the homogeneous parts of degree $\rho$ in this equation we see that either $J_F \in I$, which is equivalent to the $F_i$ having a non-trivial common zero (this does not happen generically), or the coefficient of $J_F$ (the global residue of $h$) is zero. \( \square \)

3. Global residues in $\mathbb{T}^n$ and sparse polynomial interpolation

Now we will consider sparse polynomial systems and define the global residue in this situation. The word “sparse” indicates that instead of fixing the degrees of the polynomials we fix their Newton polytopes. The Newton polytope $\Delta(f)$ of a (Laurent) polynomial $f$ is defined as the convex hull in $\mathbb{Z}^n$ of the exponent vectors of all the monomials appearing in $f$. Note that the Newton polytope of a generic polynomial of degree $d$ is a $d$-dilate of the standard $n$-simplex. Such polynomials are usually called dense. In what follows when we say generic sparse polynomial we will mean that its Newton polytope is fixed and the coefficients are generic.

Let $f_1, \ldots, f_n \in \mathbb{C}[t_1^{\pm 1}, \ldots, t_n^{\pm 1}]$ be Laurent polynomials whose Newton polytopes $\Delta_1, \ldots, \Delta_n$ are $n$-dimensional. We will assume that the solution set $Z_f \subset \mathbb{T}^n$ of the system $f_1 = \cdots = f_n = 0$ is finite. Here $\mathbb{T}^n$ denotes the $n$-dimensional algebraic torus $(\mathbb{C} - \{0\})^n$.

Like in the affine case define the global residue of a Laurent polynomial $g$ as the sum of the local Grothendieck residues
\[ R_f^T(g) = \sum_{a \in Z_f} \text{res}_a \left( \frac{g}{f_1 \cdots f_n} \frac{dt_1}{t_1} \wedge \cdots \wedge \frac{dt_n}{t_n} \right). \]

When the roots of the system are simple we obtain
\[ \mathcal{R}_{f}^{T}(g) = \sum_{a \in Z_{f}} \frac{g(a)}{J_{f}^{T}(a)}, \]

where \( J_{f}^{T} = \det\left(t_{j} \frac{\partial}{\partial x_{j}}\right) \) is the toric Jacobian of the polynomials \( f_1, \ldots, f_n \).

Notice that \( \mathcal{R}_{f}^{T}(g) \) is a linear function on the space of Laurent polynomials and depends rationally on the coefficients of \( f_i \), since it is symmetric in the roots \( Z_{f} \). In Section 5 we will give an algorithm for computing \( \mathcal{R}_{f}^{T}(g) \) as a rational function of the coefficients of the system.

The following theorem due to A. Khovanskii is a far reaching generalization of the Euler–Jacobi theorem.

**Theorem 3.1 ([13]).** Let \( f_1 = \cdots = f_n = 0 \) be a generic system of Laurent polynomials with \( n \)-dimensional Newton polytopes \( \Delta_1, \ldots, \Delta_n \). Let \( \Delta = \Delta_1 + \cdots + \Delta_n \) be the Minkowski sum. Then

1. (Toric Euler–Jacobi) for any Laurent polynomial \( h \) whose Newton polytope lies in the interior of \( \Delta \) the global residue \( \mathcal{R}_{f}^{T}(h) \) is zero;
2. (Inversion of Toric Euler–Jacobi) for any \( \phi : Z_{f} \to \mathbb{C} \) with \( \sum_{a \in Z_{f}} \phi(a) = 0 \) there exists a polynomial \( h \) whose Newton polytope lies in the interior of \( \Delta \) such that \( \phi(a) = h(a)/J_{f}^{T}(a) \).

Let us denote by \( S_{\Delta} \) the vector space of all Laurent polynomials whose Newton polytope lies in the interior \( \Delta^o \) of \( \Delta \). We have a linear map

\[ \mathcal{A} : S_{\Delta} \to \mathbb{C}^{\left|\mathbb{N}^{n}\right|}, \quad h \mapsto \left( \frac{h(a)}{J_{f}^{T}(a)}, a \in Z_{f} \right). \] *(3.1)*

Then the above theorem says that the image of \( \mathcal{A} \) is the hyperplane \( \{ \sum x_i = 0 \} \) in \( \mathbb{C}^{\left|\mathbb{N}^{n}\right|} \). By Bernstein’s theorem the number of solutions \( |Z_f| \) is equal to the normalized mixed volume \( n! V(\Delta_1, \ldots, \Delta_n) \) of the polytopes [2]. We thus obtain a lower bound on the number of interior lattice points of Minkowski sums.

**Corollary 3.2.** Let \( \Delta_1, \ldots, \Delta_n \) be \( n \)-dimensional lattice polytopes in \( \mathbb{R}^n \) and \( \Delta \) their Minkowski sum. Then the number of lattice points in the interior of \( \Delta \) is at least \( n! V(\Delta_1, \ldots, \Delta_n) - 1 \).

It would be interesting to give a direct geometric proof of this inequality and determine all collections \( \Delta_1, \ldots, \Delta_n \) for which the bound is attained. In the unmixed case \( \Delta_1 = \cdots = \Delta_n = \Delta \) the inequality becomes

\[ (n\Delta)^{o} \cap \mathbb{Z}^{n} \geq n! V_{\text{lin}}(\Delta) - 1 \] *(3.2)*

and can be deduced from Stanley’s positivity theorem for the Ehrhart polynomial [15]. Recently Batyrev and Nill described all possible \( \Delta \) which give equality in (3.2) (see [1]). Here is a mixed case example which shows that the bound in Corollary 3.2 is sharp.

**Example 1.** Let \( \Gamma(m) \) denote the simplex defined as the convex hull in \( \mathbb{R}^n \) of \( n + 1 \) points \( \{0, e_1, \ldots, e_{n-1}, me_n\} \), where \( e_i \) is the \( i \)-th standard basis vector.

Consider a collection of \( n \) such simplices \( \Gamma(m_1), \ldots, \Gamma(m_n) \) with \( m_1 \leq \cdots \leq m_n \). It is not hard to see that their mixed volume equals \( m_n \). For example, one can consider a generic system with these Newton polytopes and eliminate all but the last variable to obtain a univariate polynomial of degree \( m_n \). The number of solutions of such a system is \( m_n \), which is the mixed volume by Bernstein’s theorem.

Also one can see that the number of interior lattice points in \( \Gamma(m_1) + \cdots + \Gamma(m_n) \) is exactly \( m_n - 1 \). (In fact, these lattice points are precisely the points \( (1, \ldots, 1, k) \) for \( 1 \leq k < m_n \).)

**Corollary 3.3 (Sparse Polynomial Interpolation).** Let \( f_1 = \cdots = f_n = 0 \) be a generic system with \( n \)-dimensional Newton polytopes \( \Delta_1, \ldots, \Delta_n \) and let \( \Delta \) be their Minkowski sum. Let \( Z_{f} \subset \mathbb{N}^{n} \) denote the solution set of the system. Then for any function \( \phi : Z_{f} \to \mathbb{C} \) there is a polynomial \( g \) with \( \Delta(g) \subseteq \Delta \) such that \( g(a) = \phi(a) \). Moreover, \( g \) can be chosen to be of the form \( g = h + cJ_{f}^{T} \) for some \( h \) with \( \Delta(h) \subset \Delta^o \) and a constant \( c \).
Theorem 3.1 is an instance of a more general result. Let \( f_1, \ldots, f_k \) be generic Laurent polynomials with \( n \)-dimensional Newton polytopes \( \Delta_1, \ldots, \Delta_k \), for \( k \leq n \). The set of their common zeros defines an algebraic variety \( Z_k \) in \( \mathbb{T}^n \). There is a way to embed \( \mathbb{T}^n \) into a projective toric variety \( X \) so that the algebraic closure of \( f_i = 0 \) defines a Cartier divisor \( D_i \) on \( X \) and the closure \( Z_k \) is a complete intersection in \( X \). In [12] Khovanskii described the space of top degree holomorphic forms on \( Z_k \). The special case \( k = n \) corresponds to the space of all functions on the finite set \( Z_n = Z_f \) whose description we gave in Theorem 3.1. It follows from cohomology computation on complete intersections. In particular, for \( k = n \), there is an exact sequence of global sections

\[
\cdots \rightarrow H^0(X, \mathcal{O}(D - D_l + K)) \rightarrow H^0(X, \mathcal{O}(D + K)) \rightarrow \mathbb{C}^{\vert Z_f \vert} \rightarrow \mathbb{C} \rightarrow 0.
\]

Here \( D = D_1 + \cdots + D_n \), \( K \) the canonical divisor, and \( \mathcal{O}(L) \) the invertible sheaf corresponding to a divisor \( L \). The first non-zero map in (3.3) (from the right) is the trace map, the second map is the residue map we considered in (3.1), and the third one is given by \( (f_1, \ldots, f_n) \).

4. Some commutative algebra

As before consider a system of Laurent polynomial equations \( f_1 = \cdots = f_n = 0 \) whose Newton polytopes \( \Delta_1, \ldots, \Delta_n \) are full-dimensional. For generic coefficients the system will have a finite number of simple roots \( Z_f \) in the torus \( \mathbb{T}^n \). We concentrate on the following problem:

**Problem 2.** Given a Laurent polynomial \( g \) compute the global residue \( R_f^T(g) \) as a rational function of the coefficients of the \( f_i \).

We postpone the algorithm to the next section and now formulate our main tool for solving the problem.

**Theorem 4.1.** Let \( \Delta_0, \ldots, \Delta_n \) be \( n+1 \) full-dimensional lattice polytopes in \( \mathbb{R}^n \) and assume that \( \Delta_0 \) contains the origin in its interior. Put

\[
\tilde{\Delta} = \Delta_0 + \cdots + \Delta_n \quad \text{and} \quad \tilde{\Delta}(i) = \Delta_0 + \cdots + \Delta_{i-1} + \Delta_{i+1} + \cdots + \Delta_n.
\]

Then for generic polynomials \( f_i \) with Newton polytopes \( \Delta_i \), for \( 1 \leq i \leq n \), the linear map

\[
\bigoplus_{i=0}^n S_{\Delta(i)} \oplus \mathbb{C} \rightarrow S_{\tilde{\Delta}}^0, \quad (h_0, \ldots, h_n, c) \mapsto h_0 + \sum_{i=1}^n h_i f_i + c J_f^T
\]

is surjective.

**Proof.** Let \( g \) be in \( S_{\tilde{\Delta}}^0 \). By Corollary 3.3 there exists a polynomial \( h_0 \) supported in \( \Delta^0 = \tilde{\Delta}_{\emptyset} \) and a constant \( c \) such that \( g(a) = h_0(a) + c J_f^T(a) \) for all \( a \in Z_f \), i.e. the polynomial \( g - h_0 - c J_f^T \in S_{\tilde{\Delta}}^0 \) vanishes on \( Z_f \). Now the statement follows from Theorem 4.2 below. \( \square \)

The following statement can be considered as the toric version of the classical Noether theorem in \( \mathbb{P}^n \) (see [16], Section 20.2).

**Theorem 4.2.** Let \( f_1, \ldots, f_n \) be generic Laurent polynomials with \( n \)-dimensional Newton polytopes \( \Delta_1, \ldots, \Delta_n \). Let \( h \) be a Laurent polynomial vanishing on \( Z_f \). Assume \( \Delta(h) \) lies in the interior of \( \tilde{\Delta} = \Delta_0 + \Delta_1 + \cdots + \Delta_n \) for some \( n \)-dimensional polytope \( \Delta_0 \). Then \( h \) can be written in the form
\[ h = h_1 f_1 + \cdots + h_n f_n, \quad \text{with } \Delta(h_i) \subset \tilde{\Delta}_{(i)}, \]

where \( \tilde{\Delta}_{(i)} \) as in (4.1).

**Proof.** First we note that the statement remains true when \( \Delta_0 = \{0\} \), i.e. \( h \) is supported in the interior of \( \Delta = \Delta_1 + \cdots + \Delta_n \). This follows from the exact sequence (3.3). Indeed, if one considers the toric variety \( X \) associated with \( \Delta \) then each \( f_i \) defines a semiample divisor \( D_i \) on \( X \) with polytope \( \Delta_i \). It is well known that for any semiample divisor \( L \)

\[ H^{n-\dim \Delta_i}(X, \mathcal{O}(L + K)) \cong S_{\Delta_i}, \tag{4.3} \]

where \( \Delta_i \) is the polytope of \( L \) (see, for example [11,8]). Thus the first term in (3.3) is isomorphic to \( S_{\Delta_{(i)}} \oplus \cdots \oplus S_{\Delta_{(n)}} \), where \( \Delta_{(i)} = \sum_{j \neq i} \Delta_j \). Since the sequence is exact \( h \) lies in the kernel of the second map we get the required representation.

Now assume \( \Delta_0 \) is \( n \)-dimensional. Let \( X \) be the toric variety associated with \( \tilde{\Delta} \). Let \( f_0 \) be any monomial supported in \( \Delta_0 \). Then \( f_0, \ldots, f_n \) define \( n+1 \) semiample divisors \( D_0, \ldots, D_n \) on \( X \) whose polytopes are \( \Delta_0, \ldots, \Delta_n \). Since \( f_1, \ldots, f_n \) are generic (and so all their common zeros lie in \( \mathbb{T}^n \)) and \( f_0 \) is a monomial, the divisors \( D_0, \ldots, D_n \) have empty intersection in \( X \). Then the following twisted Koszul complex of sheaves on \( X \) is exact (see [6,7]):

\[ 0 \to \mathcal{O}(K) \to \bigoplus_{i=0}^n \mathcal{O}(D_i + K) \to \cdots \to \bigoplus_{i=0}^n \mathcal{O}(D - D_i + K) \to \mathcal{O}(D + K) \to 0, \]

where \( D = D_0 + \cdots + D_n \) and \( K \) the canonical divisor on \( X \). The first few terms of the cohomology sequence are

\[ \cdots \to \bigoplus_{i=0}^n H^0(X, \mathcal{O}(D - D_i + K)) \to H^0(X, \mathcal{O}(D + K)) \to 0, \]

where the middle map is given by \( (f_0, \ldots, f_n) \). This, with the help of (4.3), provides

\[ h = h_0 f_0 + h_1 f_1 + \cdots + h_n f_n, \quad \text{where } \Delta(h_i) \subset \tilde{\Delta}_{(i)}, \]

Notice that \( h_0 \) vanishes on \( Z_f \) and is supported in the interior of \( \tilde{\Delta}_{(0)} = \Delta \). Therefore, there exist \( h'_i \) such that

\[ h_0 = h'_1 f_1 + \cdots + h'_n f_n, \quad \text{with } \Delta(h'_i) \subset \Delta_i, \]

by the previous case. It remains to note that \( \Delta(h'_i f_0) \subset \Delta_{(i)} + \Delta_0 = \tilde{\Delta}_{(i)} \). \( \square \)

**Remark 4.3.** Theorem 4.1 has interpretation in terms of the homogeneous coordinate ring \( S_X \) of the toric variety \( X \) associated with \( \tilde{\Delta} \) (see [5]). One can homogenize \( f_0, \ldots, f_n \) to get elements \( F_0, \ldots, F_n \in S_X \) of big and nef degrees. According to the Codimension Theorem of Cox and Dickenstein (see [6]) the codimension of \( I = (F_0, \ldots, F_n) \) in critical degree (corresponding to the interior of \( \Delta \)) equals 1. Then Theorem 4.1 says that the homogenization of the Jacobian \( J(T_f) \) to the critical degree generates the critical degree part of the quotient \( S_X/I \).

5. Algorithm for computing the global residue in \( \mathbb{T}^n \)

Now we will present an algorithm for computing the global residue \( R^T_f(g) \) for any Laurent polynomial \( g \) assuming that the Newton polytopes of the system are full-dimensional.

**Algorithm 1.** Let \( f_1 = \cdots = f_n = 0 \) be a system of Laurent polynomial equations with \( n \)-dimensional Newton polytopes \( \Delta_1, \ldots, \Delta_n \). As before we let \( \Delta \) denote the Minkowski sum of the polytopes.

**Input:** A Laurent polynomial \( g \) with Newton polytope \( \Delta(g) \).

**Step 1:** Choose an \( n \)-dimensional polytope \( \Delta_0 \) with \( 0 \in \Delta_0 \) such that the Minkowski sum \( \tilde{\Delta} = \Delta_0 + \Delta \) contains \( \Delta(g) \) in its interior.
Step 2: Solve the system of linear equations

\[ g = h_0 + \sum_{i=1}^{n} h_i f_i + cJ_f^T \]

for \( c \), where \( h_i \) are polynomials with unknown coefficients supported in the interior of \( \tilde{\Delta}_{(i)} \) (see (4.1)).

Output: The global residue \( \mathcal{R}_f^T(g) = c n! V(\Delta_1, \ldots, \Delta_n) \).

Proof. According to Theorem 4.1, given \( g \) with \( \Delta(g) \subset \tilde{\Delta}^\circ \) there exist \( h_i \) supported in \( \tilde{\Delta}^\circ_{(i)} \) and \( c \in \mathbb{C} \) such that

\[ g = h_0 + \sum_{i=1}^{n} h_i f_i + cJ_f^T. \]

Taking the global residue we have

\[ \mathcal{R}_f^T(g) = \mathcal{R}_f^T(h_0) + \mathcal{R}_f^T \left( \sum_{i=1}^{n} h_i f_i \right) + c\mathcal{R}_f^T(J_f^T) = cn! V(\Delta_1, \ldots, \Delta_n), \]

where the first two terms vanish by Theorem 3.1(1) and the definition of the global residue. \( \square \)

Remark 5.1. Notice that we can ignore those terms of \( J_f^T \) whose exponents lie in the interior of \( \Delta \) since their residue is zero by Theorem 3.1(1), and work with the “restriction” of \( J_f^T \) to the boundary of \( \Delta \).

We illustrate the algorithm with a small 2-dimensional example.

Example 2. Consider a system of two equations in two unknowns.

\[
\begin{align*}
    f_1 &= a_1 x + a_2 y + a_3 x^2 y^2, \\
    f_2 &= b_1 x + b_2 xy^2 + b_3 x^2 y^2.
\end{align*}
\]

The Newton polytopes \( \Delta_1, \Delta_2 \) and their Minkowski sum \( \Delta \) are depicted in Fig. 1.

![Fig. 1. The Newton polygons and their Minkowski sum.](image)

We compute the global residue of \( g = x^5 y^4 \). Let \( \Delta_0 \) be the triangle with vertices \((-1, 0), (0, -1) \) and \((2, 1)\). Then the Minkowski sum \( \tilde{\Delta} = \Delta + \Delta_0 \) contains \( \Delta(g) = (5, 4) \) in the interior (see Fig. 2).

![Fig. 2. The Minkowski sum of \( \Delta \) and \( \Delta_0 \) contains \( \Delta(g) \) in the interior.](image)
The vector space $S_{\Delta_0}$ has dimension 15 and a monomial basis
\[ S_{\Delta_0} = \langle xy, xy^2, xy^3, x^2, x^2 y, x^2 y^2, x^2 y^3, x^3, x^3 y, x^3 y^2, x^3 y^3, x^4, x^4 y, x^4 y^2, x^4 y^3, x^5, x^5 y, x^5 y^2 \rangle. \]

Now $\Delta_0 = \Delta_1 + \Delta_2 = \Delta$, $\Delta_0(1) = \Delta_0 \cup \Delta_2$ and $\Delta_0(2) = \Delta_0 \cup \Delta_1$ and the corresponding vectors spaces are of dimension 4, 6 and 6, respectively. Here are their monomial bases:
\[
S_{\Delta_0(0)} = \langle x^2, x^2 y, x^2 y^2, x^3, x^3 y, x^3 y^2 \rangle, \quad S_{\Delta_0(1)} = \langle x, xy, x^2 y, x^2 y^2, x^3 y, x^3 y^2 \rangle, \quad S_{\Delta_0(2)} = \langle y, x, xy, x^2 y, x^2 y^2, x^3 y^2 \rangle,
\]
as Fig. 3 shows.

![Fig. 3. The polygons $\Delta_{(i)}$.](image)

We have
\[
J_f^T = -a_2 b_1 x y - a_2 b_2 x y^3 + 2 a_1 b_2 x^2 y^2 - 2 a_2 b_3 x^2 y^3 + 2 (a_1 b_3 - a_3 b_1) x^3 y^2 + 2 a_3 b_2 x^3 y^4,
\]
where we can ignore the third and the fourth terms (see Remark 5.1). Now the map (4.2) written in the above bases has the following $15 \times 17$ matrix, which we denote by $A$.

\[
\begin{bmatrix}
0 & 0 & 0 & 0 & a_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & a_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & a_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & a_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & a_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & a_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & a_1 & 0 & a_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & a_2 & 0 & b_3 & 0 & b_2 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & a_1 & 0 & 0 & 0 & 0 & 0 & 0 & b_1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & a_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & b_1 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & a_3 & 0 & 0 & 0 & a_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & a_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & a_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & a_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}.
\]

It remains to solve the system $A c = b$, where $c$ is the vector of unknowns (the coefficients of the $h_i$ and $e$) and $b$ is the monomial $g = x^5 y^4$ written in the basis for $S_{\Delta_0}$, i.e. $b = (0, \ldots, 0, 1)'$. With the help of Maple we obtain
\[
c = \frac{1}{4} \frac{a_1^2 b_2}{a_3 (a_1 b_3 - a_3 b_1)^2}.
\]
Since the mixed volume (area) of $\Delta_1$ and $\Delta_2$ equals 4, we conclude that
\[
\mathcal{R}_f^T(x^5 y^4) = \frac{a_1^2 b_2}{a_3 (a_1 b_3 - a_3 b_1)^2}.
\]
6. Some geometry

The first step of our algorithm is constructing a lattice $n$-dimensional polytope $\Delta_0$ such that the Minkowski sum $\tilde{\Delta} = \Delta_0 + \Delta$ contains both $\Delta$ and $\Delta(g)$ in its interior. There are many ways of doing that. For example, one can take $\Delta_0$ to be a sufficiently large dilate of $\Delta$ (translated so it contains the origin in the interior). In general, this could result in an unnecessarily large dimension of $S_{\Delta_0}$, which determines the size of the linear system (5.1). Therefore, to minimize the size of the linear system one would want to solve the following problem.

**Problem 3.** Given two lattice polytopes $\Delta$ and $\Delta'$ in $\mathbb{R}^n$, $\dim \Delta = n$, find an $n$-dimensional lattice polytope $\Delta_0$ such that $\Delta + \Delta_0$ contains both $\Delta$ and $\Delta'$ in its interior and has the smallest possible number of interior lattice points.

This appears to be a hard optimization problem. Instead we will consider a less challenging one. First, since the global residue is linear we can assume that $g$ is a monomial, i.e. $\Delta(g)$ is a point.

**Problem 4.** Given a convex polytope $\Delta$ and a point $u$ in $\mathbb{R}^n$ find a segment $I$ starting at the origin such that $u$ is contained in the Minkowski sum $\Delta + I$ and the volume of $\Delta + I$ is minimal.

If $I = [0, m]$, for $m \in \mathbb{Z}^n$, is such a segment then we can take $\Delta_0$ to be a “narrow” polytope with 0 in the interior and $m$ one of the vertices, as in Fig. 2. Then the volume (and presumably the number of interior lattice points) of $\tilde{\Delta} = \Delta + \Delta_0$ will be relatively small.

We will now show how Problem 4 can be reduced to a linear programming problem. Let $\Delta \subset \mathbb{R}^n$ be an $n$-dimensional polytope, $I = [0, v]$ a segment, $v \in \mathbb{R}^n$. First, notice that the volume of $\Delta + I$ equals

$$\text{Vol}_n(\Delta + I) = \text{Vol}_n(\Delta) + |I| \cdot \text{Vol}_{n-1}(\text{pr}_I \Delta),$$

where $\text{pr}_I \Delta$ is the projection of $\Delta$ onto the hyperplane orthogonal to $I$, $\text{Vol}_k$ the $k$-dimensional volume, and $|I|$ the length of $I$. For each facet $\Gamma \subset \Delta$ let $n_\Gamma$ denote the outer normal vector whose length equals the $(n-1)$-dimensional volume of $\Gamma$. Then we can write

$$|I| \cdot \text{Vol}_{n-1}(\text{pr}_I \Delta)) = \frac{1}{2} \sum_{\Gamma \subset \Delta} |(n_\Gamma, v)|.$$

But the latter is the support function $h_Z$ of a convex polytope (zonotope) $Z$, which is the Minkowski sum of segments:

$$h_Z(v) = \sum_{\Gamma \subset \Delta} |(n_\Gamma, v)|, \quad Z = \sum_{\Gamma \subset \Delta} [-n_\Gamma, n_\Gamma].$$

Indeed, $h_Z$ is the sum of the support functions of the segments. Also it is clear that

$$h_{[-n_\Gamma, n_\Gamma]}(v) = \max_{-1 \leq t \leq 1} (tn_\Gamma, v) = |(n_\Gamma, v)|.$$

An example of the polytopes $\Delta$ and $Z$, and the normal fan $\Sigma_Z$ of $Z$ is given in Fig. 4.

![Fig. 4. The zonotope Z associated with Δ and its normal fan ΣZ.](image)
Now we get back to Problem 4. After translating everything by $-u$ we may assume that $u$ is at the origin. Then Problem 4 is equivalent to finding $x \in \Delta$ such that the volume of $\Delta + [0, -x]$ is minimal, which by the previous discussion means minimizing the support function $h_Z(-x) = h_Z(x)$ on $\Delta$.

We can interpret this geometrically. The function $h_Z$ is a non-negative continuous function, linear on every cone of the normal fan $\Sigma_Z$. Its graph above the polytope $\Delta$ is a “convex down” polyhedral set in $\mathbb{R}^{n+1}$ (see Fig. 5). The set of points with the smallest last coordinate is a face of this polyhedral set. The projection of this face to $\Delta$ gives the solution to our minimization problem.

![Fig. 5. The graph of $h_Z$ above the polytope $\Delta$.](image)

Finally, note that the normal fan $\Sigma_Z$ has a simple description. It is obtained by translating all the facet hyperplanes $H_\Gamma$, for $\Gamma \subset \Delta$, to the origin.

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