SOLVING DECOMPOSABLE SPARSE SYSTEMS

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Abstract. Améndola et al. proposed a method for solving systems of polynomial equations lying in a family which exploits a recursive decomposition into smaller systems. A family of systems admits such a decomposition if and only if the corresponding Galois group is imprimitive. When the Galois group is imprimitive we consider the problem of computing an explicit decomposition. A consequence of Esterov’s classification of sparse polynomial systems with imprimitive Galois groups is that this decomposition is obtained by inspection. This leads to a recursive algorithm to solve decomposable sparse systems, which we present and give evidence for its efficiency.

Introduction

The Galois group of a univariate polynomial exposes its internal symmetry and controls its solvability by radicals. More generally, families of polynomial systems (and of geometric problems) have Galois groups [12] which expose their internal symmetry. We describe how to solve a polynomial system using numerical homotopy continuation [20, 25] by exploiting the structure of a family to which it belongs.

A family of polynomial systems (geometric problems) is represented as a branched cover of algebraic varieties $\pi: X \rightarrow Z$ where $Z$ parameterizes the family and the fiber over $z \in Z$ consists of solutions to the corresponding instance. Removing the branch locus gives a covering space whose monodromy group is a Galois group [12] of a field extension. Pirola and Schlesinger [23] observed that the Galois group acts imprimitively if and only if after replacing $Z$ by a dense open subset $V$, the branched cover factors as a composition

$$\pi^{-1}(V) \rightarrow Y \rightarrow V$$

of non-trivial branched covers, in which case $\pi$ is decomposable. Améndola et al. [1] explained how to use an explicit decomposition to compute fibers $\pi^{-1}(z)$ using monodromy [7]. They also showed how several examples from the literature involve a decomposable branched cover; for these, the variety $Y$ and intermediate maps were determined using invariant theory as there was a finite group acting as automorphisms of $\pi: X \rightarrow Z$. In general, it is nontrivial to determine a decomposition [1] of a branched cover $\pi: X \rightarrow Z$ with imprimitive Galois group, especially when the cover has trivial automorphism group.

Esterov [8] determined which systems of sparse polynomials have an imprimitive Galois group. One goal was to classify those which are solvable by radicals. He identified two

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simple structures which imply that the system is decomposable. In these cases, the decomposition is transparent. He also showed that the Galois group is full symmetric when neither structure occurs. We use Esterov’s classification to give a recursive numerical homotopy continuation algorithm for solving decomposable sparse systems.

The first such structure is when a polynomial system is composed with a monomial map, such as \( g(x^3) = 0 \). To solve this, first solve \( g(y) = 0 \) and then extract third roots of each solution. The second structure is when the system is triangular, such as

\[
 f(x, y) = g(y) = 0 .
\]

To solve this, first solve \( g(y) = 0 \) and then for each solution \( y \), solve \( f(x, y) = 0 \).

In general, Esterov’s classification leads to a sequence of branched covers, each corresponding to a sparse system with symmetric monodromy or to a monomial map. Our algorithm identifies this structure and uses it to recursively solve a decomposable system. We give some examples which demonstrate that, despite its overhead, this algorithm is a significant improvement over a direct use of the polyhedral homotopy [15, 28].

By the Bernstein-Kushnirenko Theorem [3, 17], a general system of sparse polynomials has the same number of solutions as a system whose supports have the same convex hull. When the system supported on the vertices is decomposable, we propose using it as a start system in a parameter homotopy to solve the original system. This is similar in spirit to the Bézout or total degree homotopy [10].

In Section 1 we present some general background on Galois groups of branched covers and explain the relation between decompositions of the branched cover and imprimitivity of the Galois group, finishing with a discussion of how to obtain an explicit decomposition. We specialize to decomposable sparse systems in Section 2, where we explain Esterov’s classification and describe how to compute the corresponding decompositions. We present our algorithms for solving sparse decomposable systems in Section 3, and give an application to furnish start systems for parameter homotopies. Section 4 gives timings and information on the performance of our algorithm.

1. Branched covers, Galois groups, and decomposable projections

We sketch some mathematical background, first explaining how Galois groups arise from branched covers and the relationship between imprimitive Galois groups and decompositions of the branched cover. We then discuss how to compute a decomposition when the Galois group is imprimitive.

1.1. Galois groups. Let \( \pi: X \to Z \) be a dominant map (\( \pi(X) \) is dense in \( Z \)) of irreducible complex algebraic varieties of the same dimension. Such a map is a branched cover. There exists a number \( d \) and a dense open subset \( U \subset Z \) such that for each \( z \in U \), \( \pi^{-1}(z) \) consists of \( d \) points. The branched cover is trivial when \( d = 1 \). We define two subgroups of the symmetric group \( S_d \) which are well-defined up to conjugacy.

First, the map \( \pi^{-1}(U) \to U \) is a degree \( d \) covering space. This has a monodromy group which acts on a fiber \( \pi^{-1}(z) \) for \( z \in U \) as follows [22, Ch. 13]. Given a loop \( \gamma \) in \( U \) based at \( z \), the lifts of \( \gamma \) give \( d \) paths in \( X \) connecting points of \( \pi^{-1}(z) \), and thus a permutation of
\( \pi^{-1}(z) \). The collection of all such monodromy permutations forms the monodromy group of \( \pi \), which acts transitively because \( \pi^{-1}(U) \) is connected as \( X \) is irreducible.

Second, as \( \pi: X \to Z \) is dominant, the field \( \mathbb{C}(Z) \) of rational functions on \( Z \) is a subfield of \( \mathbb{C}(X) \). Since \( \pi \) has degree \( d \), \( \mathbb{C}(X) \) is a degree \( d \) extension of \( \mathbb{C}(Z) \). If \( K \) is the Galois closure of \( \mathbb{C}(X)/\mathbb{C}(Z) \), then the Galois group \( G_\pi \) of the branched cover \( \pi: X \to Z \) is the Galois group of \( K/\mathbb{C}(Z) \). Harris [12] gave a modern proof that the Galois group equals the monodromy group, but this idea goes back at least to Hermite [14].

We recall some terminology concerning permutation groups [29]. Suppose that \( G \) acts on a subset \( B \subset \mathbb{C}(Z) \). A block of \( G \) is a permutation group acting transitively on the set \( \{1, 2, \ldots, d\} \). If \( \ker G \) is a subgroup properly containing \( G \), then \( G \) is decomposable if and only if its Galois group equals the monodromy group, but this idea goes back at least to Hermite [14].

We give a proof, as we discuss the problem of computing a decomposition.

We observe a second characterization of imprimitive permutation groups \( G \). Since \( G \) acts transitively, if \( H \subset G \) is the stabilizer of a point \( c \in \{d\} \), then \( H \) has index \( d \) in \( G \) and we may identify \( \{d\} \) with the cosets \( G/H \). If \( B \) is a nontrivial block of \( G \) containing \( c \), then its stabilizer \( L \) is a proper subgroup of \( G \) that strictly contains \( H \). Furthermore, using the map \( G/H \to G/L \), we see that \( G \) is imprimitive if and only if the stabilizer of the point \( eH \subset G/H \) is not a maximal subgroup.

### 1.2. Decomposable branched covers.

A branched cover \( \pi: X \to Z \) is decomposable if there is a dense open subset \( V \subset Z \) over which \( \pi \) factors

\[
\pi^{-1}(V) \xrightarrow{\varphi} Y \xrightarrow{\psi} V,
\]

with \( \varphi \) and \( \psi \) both nontrivial branched covers. The fibers of \( \varphi \) over points of \( \psi^{-1}(v) \) are blocks of the action of \( G_\pi \) on \( \pi^{-1}(v) \), which implies that \( G_\pi \) is imprimitive. Pirola and Schlesinger [23] observed that decomposability of \( \pi \) is equivalent to imprimitivity of \( G_\pi \). We give a proof, as we discuss the problem of computing a decomposition.

**Proposition 1.** A branched cover is decomposable if and only if its Galois group is imprimitive.

**Proof.** We need only to prove the reverse direction. As above, let \( \mathbb{C}(Z), \mathbb{C}(X), \) and \( K \) be the function fields of \( Z, X, \) and the Galois closure of \( \mathbb{C}(X)/\mathbb{C}(Z) \), respectively, and let \( G_\pi \) be the Galois group of \( K/\mathbb{C}(Z) \). Let \( H \) be the subgroup of \( G_\pi \) such that \( \mathbb{C}(X) = K^H \), the fixed field of \( H \). The set of Galois conjugates of \( \mathbb{C}(X) \) forms the orbit \( G_\pi/H \), and the number of conjugates is the degree of the branched cover \( X \to Z \).

If \( G_\pi \) acts imprimitively, then the stabilizer \( L \) of a nontrivial block \( B \) containing \( \mathbb{C}(X) \) is a proper subgroup properly containing \( H \). Thus its fixed field \( M := K^L \), which is the intersection of the conjugates of \( \mathbb{C}(X) \) in the block \( B \), is an intermediate field between
\( \mathbb{C}(Z) \) and \( \mathbb{C}(X) \). For any variety \( Y' \) with function field \( M \), there will be dense open subsets \( Y \) of \( Y' \) and \( V \) of \( Z \) such that (2) holds.

While imprimitivity is equivalent to decomposability, the proof does not address how to compute the variety \( Y \) of (2). One way is as follows. Replace \( Z \) and \( X \) by affine open subsets, if necessary, and let \( y_1, \ldots, y_m \in \mathbb{C}[X] \) be regular functions on \( X \) that generate \( M \) over \( \mathbb{C}(Z) \). Let \( x_1, \ldots, x_m \) be indeterminates and let \( I \subset \mathbb{C}(Z)[x_1, \ldots, x_m] \) be the kernel of the map \( \mathbb{C}(Z)[x_1, \ldots, x_m] \to \mathbb{C}(X) \) given by \( x_i \mapsto y_i \). This is the zero-dimensional ideal of algebraic relations satisfied by \( y_1, \ldots, y_m \). Replacing \( Z \) by a dense affine open subset if necessary, we may choose generators \( g_1, \ldots, g_r \) of \( I \) that lie in \( \mathbb{C}[Z][x_1, \ldots, x_m] \)—their coefficients are regular functions on \( Z \). There is an open subset \( V \subset Z \) such that the ideal \( I \) defines an irreducible variety \( Y \subset V \times \mathbb{C}^m \) whose projection to \( V \) is a branched cover and whose function field is \( M \). Restricting \( X \to Z \) to \( V \), we obtain the desired decomposition, with the map \( X \to Y \) given by the functions \( y_1, \ldots, y_m \).

This does not address the practicality of computing \( Y \), but it does indicate an approach. Given the subgroup \( L \) of \( G_\pi \) and a set of generators of \( \mathbb{C}[X] \) over \( \mathbb{C}[Z] \), if we apply the Reynolds averaging operator \([6]\) for \( L \) to monomials in the generators, we obtain the desired generators \( y_1, \ldots, y_m \) of \( M \). One problem is that elements of \( G_\pi \) may not act on \( X \), so their action on elements of \( \mathbb{C}[X] \) may be hard to describe.

There is an exception to this. If \( L \neq H \) normalizes \( H \) in \( G \) and \( \pi : X \to Z \) is a covering space, then \( \Gamma := L/H \) acts freely on \( X \), preserving the fibers—it is a group of deck transformations of \( X \to Z \) \([22\text{, Ch }13]\). When \( \Gamma \) acts on the original branched cover, \( Y = X/\Gamma \) is the desired space, and both \( Y \) and the map \( X \to Y \) may be computed by applying the Reynolds operator for \( \Gamma \) to generators of \( \mathbb{C}[X] \). The examples given in \([1\text{, }\S\ 5]\) are of this form, and the authors use this approach to compute the decomposition (2).

**Example 2.** Not all imprimitive groups have this property. Consider the wreath product \( G := S_3 \wr S_3 \), which acts imprimitively on the nine-element set \( [3] \times [3] \). The stabilizer of the point \((3, 3)\) is the subgroup \( H = ((S_3)^2 \times S_3) \rtimes S_2 \), where \( S_2 \subset S_3 \) is the stabilizer of \( \{3\} \). Then \( H \) is its own normalizer in \( G \), as \( S_2 \) is its own normalizer in \( S_3 \).

All imprimitive Galois groups in the Schubert calculus constructed in \([19\text{, }\S\ 3]\) and in \([26]\) have the stabilizer \( H \) equal to its normalizer. For these, the decomposition of the branched cover follows from a deep structural understanding of the corresponding Schubert problem. There remain many Schubert problems whose Galois group is expected to be imprimitive, yet we do not know a decomposition (2) of the corresponding branched cover.

The structure of imprimitivity/decomposability found in \([19\text{, }26]\) was not initially apparent, and further study was needed to determine a decomposition. In contrast, a consequence of Esterov’s study of Galois groups of sparse polynomial systems is that decomposability is transparent and may be deduced by inspection, as well as the decomposition (2).

This is explained in the following section.

### 2. Decomposable Sparse Systems

We discuss sparse systems of (Laurent) polynomials and interpret them as branched covers. Then we state the Bernstein-Kushinrenko Theorem for their numbers of solutions,
and give the relation between integer linear algebra and maps of algebraic tori. We then present Esterov’s criteria for imprimitivity, and show how these criteria lead to decompositions of the corresponding branched cover.

2.1. Sparse Polynomial Systems. Let $\mathbb{C}^\times := \mathbb{C} \setminus \{0\}$ be the multiplicative group of nonzero complex numbers and $(\mathbb{C}^\times)^n$ be the $n$-dimensional complex torus. For each $\alpha = (\alpha_1, \ldots, \alpha_n) \in \mathbb{Z}^n$, the (Laurent) monomial with exponent $\alpha$,

$$x^\alpha := x_1^{\alpha_1} x_2^{\alpha_2} \cdots x_n^{\alpha_n},$$

is a character (multiplicative map) $x^\alpha : (\mathbb{C}^\times)^n \rightarrow \mathbb{C}^\times$. A finite linear combination

$$f = \sum c_\alpha x^\alpha \quad c_\alpha \in \mathbb{C}$$

of monomials is a (Laurent) polynomial, which is a function $f : (\mathbb{C}^\times)^n \rightarrow \mathbb{C}$.

For a nonempty finite set $A \subset \mathbb{Z}^i$, the set of polynomials $[3]$ satisfying $c_\alpha \neq 0 \Rightarrow \alpha \in A$ is the vector space $\mathbb{C}^A$ of polynomials of support $A$. Given a collection $A_\bullet := (A_1, \ldots, A_n)$ of nonempty finite subsets of $\mathbb{Z}^n$, write $\mathbb{C}^{A_\bullet} := \mathbb{C}^{A_1} \times \cdots \times \mathbb{C}^{A_n}$ for the vector space of $n$-tuples $F = (f_1, \ldots, f_n)$ of polynomials, where $f_i$ has support $A_i$, for each $i$. An element $F \in \mathbb{C}^{A_\bullet}$ corresponds to a system of polynomial equations

$$f_1(x_1, \ldots, x_n) = f_2(x_1, \ldots, x_n) = \cdots = f_n(x_1, \ldots, x_n) = 0,$$

called a sparse polynomial system of support $A_\bullet$. Its set of solutions is $\mathcal{V}(F)$. We write $F$ to refer to these equations or to their vector of coefficients, depending on context.

Given supports $A_\bullet = (A_1, \ldots, A_n)$, consider the incidence variety

$$X_{A_\bullet} := \{ (F, x) \in \mathbb{C}^{A_\bullet} \times (\mathbb{C}^\times)^n \mid F(x) = 0 \}.$$

equipped with projections $\pi : X_{A_\bullet} \rightarrow \mathbb{C}^{A_\bullet}$ and $p : X_{A_\bullet} \rightarrow (\mathbb{C}^\times)^n$. For any point $x \in (\mathbb{C}^\times)^n$, the fiber $p^{-1}(x)$ is a vector subspace of $\mathbb{C}^{A_\bullet}$ of codimension $n$. Indeed, for each $i = 1, \ldots, n$, the condition that $f_i(x) = 0$ is a linear equation in the coefficients $\mathbb{C}^{A_i}$ of $f_i$, and these $n$ linear equations are independent. Thus $X_{A_\bullet}$ is irreducible of dimension

$$\dim(\mathbb{C}^\times)^n + \dim \mathbb{C}^{A_\bullet} - n = \dim \mathbb{C}^{A_\bullet}.$$

For $F \in \mathbb{C}^{A_\bullet}$, the fiber $\pi^{-1}(F)$ is the set $\mathcal{V}(F)$ of solutions in $(\mathbb{C}^\times)^n$ to $F = 0$. The image of $X_{A_\bullet}$ under $\pi$ either lies in a proper subvariety $Z$ of $\mathbb{C}^{A_\bullet}$ or it is dense in $\mathbb{C}^{A_\bullet}$. In the first case, there is a dense open subset $U := \mathbb{C}^{A_\bullet} \setminus Z$ consisting of polynomial systems $F \in \mathbb{C}^{A_\bullet}$ with no solutions. In the second case, $\pi : X_{A_\bullet} \rightarrow \mathbb{C}^{A_\bullet}$ is a branched cover, so there is a positive integer $d$ and a dense open subset $U \subset \mathbb{C}^{A_\bullet}$ consisting of polynomial systems $F$ with $d$ solutions. Both cases are determined by the polyhedral geometry of the supports $A_\bullet$ through the Bernstein-Kushnirenko Theorem.

For convex sets $K_1, \ldots, K_n \subset \mathbb{R}^n$ and nonnegative real numbers, $t_1, \ldots, t_n \in \mathbb{R}_{\geq 0}$, Minkowski proved that the volume of the Minkowski sum

$$t_1 K_1 + \cdots + t_n K_n := \{ t_1 x_1 + \cdots + t_n x_n \mid x_i \in K_i \}$$

is a homogeneous polynomial of degree $n$ in $t_1, \ldots, t_n$. Its coefficient of $t_1 \cdots t_n$ is the mixed volume of $K_1, \ldots, K_n$. For $A_\bullet = (A_1, \ldots, A_n)$, let $\text{MV}(A_\bullet)$ be the mixed volume
of \( \text{conv}(A_1), \ldots, \text{conv}(A_n) \), where \( \text{conv}(A_i) \) is the convex hull of \( A_i \). This is described in more detail in [9, Sect. IV.3]. We give the Bernstein-Kushnirenko Theorem \[ \frac{\partial}{\partial t} \text{MV}(A) \] for \( t \to 0 \) with MV\((A_i) \) at \( t = 0 \).

Proposition 3. Let \( F \in \mathbb{C}^{A_n} \) be a system of polynomials with support \( A_n \). The number of isolated solutions in \((\mathbb{C}^\times)^n\) to \( F = 0 \) is at most \( \text{MV}(A_n) \). There is a dense open subset \( U \subset \mathbb{C}^{A_n} \) consisting of systems with exactly \( \text{MV}(A_n) \) solutions.

Thus \( \pi: X_{A_n} \to \mathbb{C}^{A_n} \) is a branched cover if and only if \( \text{MV}(A_n) \neq 0 \), which was determined by Minkowski as follows. For a nonempty subset \( I \subseteq [n] := \{1, \ldots, n\} \), write \( A_I := (A_i \mid i \in I) \) and \( \mathbb{Z}A_I \) be the affine span of the supports in \( A_I \). This is the lattice generated by differences \( \alpha - \beta \) for \( \alpha, \beta \in A_I \) for some \( i \in I \). Then \( \text{MV}(A_I) = 0 \) if and only if there exists a nonempty subset \( I \subseteq [n] \) such that \( |I| \) exceeds \( \text{rank}(\mathbb{Z}A_I) \). In particular, \( \text{MV}(A_n) \neq 0 \) implies that \( \mathbb{Z}A_n = \mathbb{Z}A_{[n]} \) has full rank \( n \).

The branched cover \( \pi: X_{A_n} \to \mathbb{C}^{A_n} \) is nontrivial when \( \text{MV}(A_n) > 1 \). Given supports \( A_n \) with \( \text{MV}(A_n) \neq 0 \), let \( G_{A_n} \) be the Galois group of the branched cover \( X_{A_n} \to \mathbb{C}^{A_n} \).

2.2. Integer linear algebra and coordinate changes. As a monomial \( x^\beta \) for \( \beta \in \mathbb{Z}^n \) is invertible on \((\mathbb{C}^\times)^n\), polynomials \( f \) and \( x^\beta f \) have the same sets of zeroes. If \( A \) is the support of \( f \), then the support of \( x^\beta f \) is \( A + \beta \), the translation of \( A \) by \( \beta \). Thus translating the supports of sparse polynomials by integer vectors does not change any assertions about their zeroes in \((\mathbb{C}^\times)^n\). Similarly, \( \mathbb{Z}A = \mathbb{Z}(\beta + A) \). Consequently, we will henceforth assume that \( 0 \in A \), for then \( \mathbb{Z}A \) will be the \( \mathbb{Z} \)-linear span of \( A \).

We identify the set \( \text{Hom}((\mathbb{C}^\times)^n, \mathbb{C}^\times) \) of characters on \((\mathbb{C}^\times)^n\) with the free abelian group \( \mathbb{Z}^n \). A group homomorphism \( \Phi: (\mathbb{C}^\times)^m \to (\mathbb{C}^\times)^k \) is determined by \( k \) characters of \((\mathbb{C}^\times)^m\), equivalently by a homomorphism (linear map) \( \varphi: \mathbb{Z}^k \to \mathbb{Z}^m \) of free abelian groups—\( \varphi \) is also the map pulling a character of \((\mathbb{C}^\times)^k \) back along \( \Phi \). In particular, an invertible map \( \Phi: (\mathbb{C}^\times)^n \to (\mathbb{C}^\times)^n \) (a monomial change of coordinates) pulls back to an invertible map \( \varphi: \mathbb{Z}^n \to \mathbb{Z}^n \), identifying \( \text{GL}(n, \mathbb{Z}) \) with the group of possible monomial coordinate changes. We will write \( \Phi = \varphi^* \) and \( \varphi = \Phi^* \) for these. If \( \Phi(x) = (x^{\alpha_1}, \ldots, x^{\alpha_m}) \) where the integer span of \( \{\alpha_1, \ldots, \alpha_m\} \) is \( \mathbb{Z}^n \), then the map \( \varphi = \Phi^*: \mathbb{Z}^n \rightarrow \mathbb{Z}^n \) sends the \( i \)-th standard basis vector \( e_i \) to \( \alpha_i \) and is represented by the invertible matrix \( A \) whose \( i \)-th column is \( \alpha_i \).

Suppose that \( f \) is a polynomial on \((\mathbb{C}^\times)^n\) with support \( A \). Given a homomorphism \( \Phi: (\mathbb{C}^\times)^m \to (\mathbb{C}^\times)^n \), the composition \( f(\Phi(z)) \) for \( z \in (\mathbb{C}^\times)^m \) is a polynomial with support \( \varphi(A) \), where the coefficient of \( z^\beta \) is the sum of coefficients of \( x^\alpha \) for \( \alpha \in \varphi^{-1}(\beta) \cap A \).

2.3. Decompositions of Sparse Polynomial Systems. We describe two properties that a collection \( A_n \) of supports may have, lacunary and (strictly) triangular, and then recall Esterov’s theorem about the Galois group \( G_{A_n} \). We then present explicit decompositions of the projection \( \pi: X_{A_n} \to \mathbb{C}^{A_n} \) when \( A_n \) is lacunary and when \( A_n \) is triangular. These form the basis for our algorithms.

Let \( A_n = (A_1, \ldots, A_n) \) be a collection of supports. Assume that \( \text{MV}(A_n) > 1 \). We say that \( A_n \) is lacunary if the affine span \( \mathbb{Z}A_n \neq \mathbb{Z}^n \) (it has rank \( n \) as \( \text{MV}(A_n) \neq 0 \)). We say that \( A_n \) is triangular if there is a nonempty proper subset \( \emptyset \neq I \subseteq [n] \) such that \( \text{rank}(\mathbb{Z}A_I) = |I| \). As we explain in Section 2.4, we may change coordinates and assume
that \( \mathbb{Z}A_i \subset \mathbb{Z}^{|I|} \) so that \( \text{MV}(A_i) \) is defined using \( \text{conv}(A_i) \subset \mathbb{R}^{|I|} \) for \( i \in I \). A system \( A_* \) of triangular supports is \textit{strictly triangular} if for some \( 0 \neq I \subset [n] \) with \( \text{rank}(\mathbb{Z}A_i) = |I| \), we have \( 1 < \text{MV}(A_i) < \text{MV}(A_*) \). It is elementary that if \( A_* \) is either lacunary or strictly triangular, then the branched cover \( X_{A_*} \to \mathbb{C}A_* \) is decomposable and therefore \( G_{A_*} \) is an imprimitive permutation group. We do this explicitly in Sections 2.3.1 and 2.3.2.

**Proposition 4** (Esterov [8]). Let \( A_* \) be a collection of supports with \( \text{MV}(A_*) \neq 0 \). The Galois group \( G_{A_*} \) is equal to the symmetric group \( S_{\text{MV}(A_*)} \) if and only if \( A_* \) is neither lacunary nor strictly triangular.

**2.3.1. Lacunary support.** Let us begin with an example when \( n = 2 \). We represent vectors by the columns of a matrix. Let

\[
A_1 := \begin{pmatrix} 0 & 0 & 3 & 6 & 12 \\ 0 & 4 & 3 & 6 & 0 \end{pmatrix} \quad \text{and} \quad A_2 := \begin{pmatrix} 0 & 3 & 6 & 9 & 9 \\ 0 & 7 & 2 & 1 & 5 \end{pmatrix}
\]

be supports in \( \mathbb{Z}^2 \). Then \( \mathbb{Z}A_* \) has index 12 in \( \mathbb{Z}^2 \) as the map \( \varphi(a, b)^T = (3a, 4b - a)^T \) is an isomorphism \( \varphi: \mathbb{Z}^2 \cong \mathbb{Z}A_* \), and \( \text{det}(\begin{pmatrix} 3 & 0 \\ -1 & 4 \end{pmatrix}) = 12 \). If we set \( B_1 := \varphi^{-1}(A_1) \), then

\[
B_1 := \begin{pmatrix} 0 & 0 & 1 & 2 & 4 \\ 0 & 1 & 1 & 2 & 1 \end{pmatrix} \quad \text{and} \quad B_2 := \begin{pmatrix} 0 & 1 & 2 & 3 & 3 \\ 0 & 2 & 1 & 1 & 2 \end{pmatrix}.
\]

We display \( A_1, A_2, B_1, \) and \( B_2 \) below.

Then the map \( \Phi := \varphi^*: (\mathbb{C}^*)^2 \to (\mathbb{C}^*)^2 \) is given by \( \Phi(x, y) = (x^3y^{-1}, y^4) = (z, w) \). If

\[
f_1 = 1 + 2y^4 + 4x^3y^3 + 8x^6y^6 + 16x^{12} \\
f_2 = 3 + 5x^3y^7 + 7x^6y^2 + 11x^9y + 13x^9y^5,
\]

which is a polynomial system with support \( A_* \), then \( f_i = g_i \circ \Phi \), where

\[
g_1 = 1 + 2w + 4zw + 8z^2w^2 + 16z^4w \\
g_2 = 3 + 5zw^2 + 7z^2w + 11z^3w + 13z^3w^2,
\]

is a polynomial system with support \( B_* \). Thus the branched cover \( X_{A_*} \to \mathbb{C}A_* \) factors \( X_{A_*} \to X_{B_*} \to \mathbb{C}B_* = \mathbb{C}A_* \) with the map \( X_{A_*} \to X_{B_*} \) induced by \( \Phi \). This implies that \( G_{A_*} \subset \mathbb{Z}/12\mathbb{Z} \times S_{10} \), as \( \mathbb{Z}^2/\mathbb{Z}A_* \cong \mathbb{Z}/12\mathbb{Z} \), \( B_* \) is neither lacunary nor triangular, and \( \text{MV}(B_*) = 10 \).

We generalize this example. Suppose that \( A_* = (A_1, \ldots, A_n) \) is lacunary. Then \( \mathbb{Z}A_* \has rank n but \( \mathbb{Z}A_* \neq \mathbb{Z}^n \). Let \( \varphi: \mathbb{Z}^n \cong \mathbb{Z}A_* \) be an isomorphism. Then the corresponding map \( \Phi = \varphi^*: (\mathbb{C}^*)^n \to (\mathbb{C}^*)^n \) is a surjection with kernel \( \text{Hom}(\mathbb{Z}^n/\mathbb{Z}A_*, \mathbb{C}^*) \). For each \( i = 1, \ldots, n \), set \( B_i := \varphi^{-1}(A_i) \). Then \( B_* = (B_1, \ldots, B_n) \) is a collection of supports with
$ZB_\bullet = Z^n$. Since $\varphi$ is a bijection, we identify $C^{B_\bullet}$ with $C^{A_\bullet}$ and $C^{B_\bullet}$ with $C^{A_\bullet}$. Given a system $F \in C^{A_\bullet}$, let $\iota(F) \in C^{B_\bullet}$ be the corresponding system with support $B_\bullet$.

**Lemma 5.** Suppose that $A_\bullet$ is lacunary, $\varphi: Z^n \xrightarrow{\sim} ZA_\bullet$ is an isomorphism with corresponding surjection $\Phi: (C^\times)^n \rightarrow (C^\times)^n$. Let $B_\bullet := \varphi^{-1}(A_\bullet)$ and suppose that $MV(B_\bullet) > 1$. Then the branched cover $X_{A_\bullet} \rightarrow C^{A_\bullet}$ is decomposable and $X_{A_\bullet} \rightarrow X_{B_\bullet} \rightarrow C^{A_\bullet} = C^{B_\bullet}$ is a nontrivial decomposition of branched covers induced by the map $\Phi$.

**Proof.** If $g$ is a polynomial with support $B \subset Z^n$, then the composition $g \circ \Phi$ is a polynomial with support $\varphi(B)$, with the coefficient of $x^\beta$ in $g$ equal to the coefficient of $x^{\varphi(\beta)}$ in $g \circ \Phi$. Since $\varphi(B_i) = A_i$, this gives the natural identifications $\iota: C^{A_i} \xrightarrow{\sim} C^{B_i}$ and $\iota: C^{A_\bullet} \xrightarrow{\sim} C^{B_\bullet}$ mentioned before the lemma. Under this identification, we have $\iota(f)(\Phi(x)) = f(x)$.

Since $MV(B_\bullet) > 1$, the branched cover $X_{B_\bullet} \rightarrow C^{B_\bullet}$ is nontrivial. The identification $\iota: C^{A_\bullet} \rightarrow C^{B_\bullet}$ extends to a commutative diagram

$$
\begin{array}{ccc}
X_{A_\bullet} & \xrightarrow{\iota \times \Phi} & X_{B_\bullet} \\
\pi & & \pi \\
C^{A_\bullet} & \xrightarrow{\iota} & C^{B_\bullet}
\end{array}
$$

Here, $\iota \times \Phi$ is the restriction of the map $\iota \times \Phi: C^{A_\bullet} \times (C^\times)^n \rightarrow C^{B_\bullet} \times (C^\times)^n$ to $X_{A_\bullet}$. The map $\iota \times \Phi: X_{A_\bullet} \rightarrow X_{B_\bullet}$ is a map of branched covers with $\ker \Phi$ acting freely on the fibers. If we restrict the diagram (4) to the open subset $V$ of $C^{B_\bullet}$ over which $X_{B_\bullet} \rightarrow C^{B_\bullet}$ is a covering space, we obtain a composition of covering spaces with $\ker \Phi$ acting as deck transformations on $\pi^{-1}(V) \subset X_{A_\bullet}$. Thus $X_{A_\bullet} \rightarrow C^{A_\bullet}$ is decomposable. □

### 2.3.2. Triangular support

This requires more discussion before we can state the analog of Lemma 5. Let us begin with an example when $n = 3$. Suppose that

$$A_1 = A_2 = A = \begin{pmatrix} 0 & 1 & 1 & 1 & 2 & 2 & 2 & 3 \\ 0 & 0 & 1 & 2 & 0 & 1 & 2 & 1 \\ 0 & 1 & 2 & 3 & 2 & 3 & 4 & 4 \end{pmatrix} \quad \text{and} \quad A_3 = \begin{pmatrix} 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 2 & 4 & 5 & 3 & 4 \end{pmatrix}$$

The span $ZA$ of the first two supports is isomorphic to $Z^2$, with $\varphi(a, b)^T \mapsto (a, b, a+b)^T$ an isomorphism $\varphi: Z^2 \xrightarrow{\sim} ZA_\bullet$. Set $B := \varphi^{-1}(A)$. We display $A$, $A_3$, and $B$ in the horizontal plane together on the left below, and $B$ on the right.
Consider the polynomial system $F = (f_1, f_2, f_3) \in \mathbb{C}[x, y, z]$ with support $\mathcal{A}$,
\[
\begin{align*}
f_1 &= 1 + 2zx + 3xyz^2 + 4xy^2z^3 + 5x^2z^2 + 6x^2y^2z + 7x^2y^2z^2 + 8x^3yz^4 \\
f_2 &= 2 + 3zx + 5xyz^2 + 7xy^2z^3 + 11x^2z^2 + 13x^2y^2z + 17x^2y^2z^2 + 19x^3yz^4 \\
f_3 &= 1 + 3x^2 + 9z^2 + 27yz^5 + 81xz^2 + 243xyz^4.
\end{align*}
\]
Let $\Phi: (\mathbb{C}^\times)^3 \to (\mathbb{C}^\times)^2$ be given by $\Phi(x, y, z) = (xz, yz)$ for $i = 1, 2$. To compute $\mathcal{V}(F)$, we first may compute $\mathcal{V}(g_1, g_2)$ which consists of eight points. For each solution $\Phi((u_0, v_0) \in \mathcal{V}(g_1, g_2)$, we may identify the fiber $\Phi^{-1}(u_0, v_0)$ with $(\mathbb{C}^\times)$ by $z \mapsto (u_0z^{-1}, v_0z^{-1}, z)$. Then the restriction of $f_3$ to this fiber is
\[
1 + (3 + 81u_0 + 243u_0v_0)z^2 + (9 + 27v_0)z^4,
\]
which is a lacunary univariate polynomial with support $\{0, 2, 4\}$, and has four solutions (counted with multiplicity) when $v_0 \neq -1/3$.

This example generalizes to all triangular systems. Suppose that $\mathcal{A} = (\mathcal{A}_1, \ldots, \mathcal{A}_n)$ is triangular. Let $\emptyset \neq I \subseteq [n]$ be a proper subset witnessing the triangularity, so that $\text{rank}(\mathbb{Z}\mathcal{A}_I) = |I|$. Set $J := [n] \setminus I$. Let
\[
\mathbb{Z}^I := \mathbb{Q}\mathcal{A}_I \cap \mathbb{Z}^n = \{v \in \mathbb{Z}^n \mid \exists m \in \mathbb{N} \text{ with } mv \in \mathbb{Z}\mathcal{A}_I\},
\]
be the saturation of $\mathbb{Z}\mathcal{A}_I$, which is a free abelian group of rank $|I|$. As it is saturated, $\mathbb{Z}_J := \mathbb{Z}^n/\mathbb{Z}^I$ is free abelian of rank $n - |I| = |J|$. Applying $\text{Hom}(\bullet, \mathbb{C}^\times)$ to the short exact sequence $\mathbb{Z}^I \hookrightarrow \mathbb{Z}^n \twoheadrightarrow \mathbb{Z}_J$ gives the short exact sequence of tori (whose characters are $\mathbb{Z}_J$, $\mathbb{Z}^n$, and $\mathbb{Z}^I$) with indicated maps,
\[
(5) \quad (\mathbb{C}^\times)^{|I|} \simeq \mathbb{T}_J := \text{Hom}(\mathbb{Z}_J, \mathbb{C}^\times) \longrightarrow (\mathbb{C}^\times)^n \xrightarrow{\Phi} \mathbb{T}^I := \text{Hom}(\mathbb{Z}^I, \mathbb{C}^\times) \simeq (\mathbb{C}^\times)^{|I|}.
\]
A polynomial $f$ with support in $\mathbb{Z}^I$ determines polynomial functions on $(\mathbb{C}^\times)^n$ and on $\mathbb{T}^I$ with the first the pullback of the second. Let $f$ be a polynomial on $(\mathbb{C}^\times)^n$ with support $\mathcal{A} \subset \mathbb{Z}^n$. Then its restriction to a fiber $\Phi^{-1}(y_0)$ of $\Phi$ is a regular function $\overline{f}$ on the fiber, which is a coset of $\mathbb{T}_J$. Choosing an identification of $\mathbb{T}_J \simeq \Phi^{-1}(y_0)$, we obtain a polynomial $\overline{f}$ on $\mathbb{T}_J$ whose support is the image $\overline{\mathcal{A}}$ of $\mathcal{A}$ in $\mathbb{Z}_J = \mathbb{Z}^n/\mathbb{Z}^I$. This polynomial $\overline{f}$ depends upon the identification of the fiber with $\mathbb{T}_J$. Let $\overline{\mathcal{A}}_J$ be the image in $\mathbb{Z}_J$ of the collection $\mathcal{A}_J$ of supports. Then we have the product formula (see [27, Lem. 6] or [8, Thm. 1.10])
\[
(6) \quad \text{MV}(\mathcal{A}_\bullet) = \text{MV}(\mathcal{A}_I) \cdot \text{MV}(\overline{\mathcal{A}}_J).
\]
Since $\mathcal{A}_\bullet = \mathcal{A}_I \sqcup \mathcal{A}_J$, we have the identification $\mathbb{C}^{\mathcal{A}_\bullet} = \mathbb{C}^{\mathcal{A}_I} \oplus \mathbb{C}^{\mathcal{A}_J}$. Suppose that $F \in \mathbb{C}^{\mathcal{A}_\bullet}$ is a polynomial system with support $\mathcal{A}_\bullet$. Write $F_I \in \mathbb{C}^{\mathcal{A}_I}$ for its restriction to the indices in $I$, and the same for $F_J$. We have the diagram
Here, $p_I \times \Phi$ is the restriction of the map $p_I \times \Phi : \mathbb{C}^{A_\bullet} \times (\mathbb{C}^*)^n \to \mathbb{C}^{A_I} \times \mathbb{T}^I$ to $X_{A_\bullet}$.

Let $V_{A_\bullet} \subset \mathbb{C}^{A_\bullet}$ be the dense open subset over which $X_{A_\bullet}$ is a covering space. This is the set of polynomial systems $F$ with support $A_\bullet$ which have exactly $\MV(A_\bullet)$ solutions in $(\mathbb{C}^*)^n$. Similarly, let $V_{A_I} \subset \mathbb{C}^{A_I}$ be the subset where $X_{A_I} \to \mathbb{C}^{A_I}$ is a covering space. We will show that under the projection $\mathbb{C}^{A_\bullet} \to \mathbb{C}^{A_I}$, the image of $V_{A_\bullet}$ is a subset of $V_{A_I}$. Define $Y_{A_\bullet} \to V_{A_\bullet}$ to be the restriction of $X_{A_\bullet} \to \mathbb{C}^{A_\bullet}$ to the dense open set $V_{A_\bullet}$. Also define $Y_{A_I} \to V_{A_I}$ to be the pullback of $X_{A_I} \to \mathbb{C}^{A_I}$ along the map $V_{A_\bullet} \to V_{A_I}$. Write $\Phi : Y_{A_\bullet} \to Y_{A_I}$ for the map induced by $\Phi$.

**Lemma 6.** Suppose that $A_\bullet$ is a triangular set of supports in $\mathbb{Z}^n$ witnessed by $I \subseteq [n]$. Then $Y_{A_\bullet} \to Y_{A_I} \to V_{A_\bullet}$ a composition of covering spaces. If $1 < \MV(A_I) < \MV(A_\bullet)$, then this decomposition is nontrivial, so that $X_{A_\bullet} \to \mathbb{C}^{A_\bullet}$ is decomposable.

Furthermore, each fiber of the map $Y_{A_\bullet} \to Y_{A_I}$ may be identified with the set of solutions to a polynomial system with support $A_J$.

**Proof.** Let $F \in V_{A_\bullet}$. Then its number of solutions is $\#V(F) = \MV(A_\bullet)$. If $x \in V(F)$, then $\Phi(x) \in \mathbb{T}^I$ is a solution to $f_i = 0$ for $i \in I$. Thus $\Phi(V(F)) \subset V(F_I)$, the latter being the solutions to $F_I$ on $\mathbb{T}^I$. For any $y \in V(F_I)$, if we choose an identification $T_I \simeq \Phi^{-1}(y)$ of the fiber, then the restriction of $F$ to $\Phi^{-1}(y)$ is the system $F_J = \{f_j \mid j \in J\}$. By the Bernstein-Kushnirenko Theorem, this has at most $\MV(A_J)$ solutions. By the product formula (6) and our assumption on $\#V(F)$, we conclude that the system $F_I$ has $\MV(A_I)$ solutions, and for each $y \in V(F_I)$, the system $F_J$ has $\MV(A_J)$ solutions.

In particular, this implies that the image of $V_{A_\bullet}$ in $\mathbb{C}^{A_I}$ is a subset of $V_{A_I}$. As $V_{A_\bullet}$ is open and dense in $\mathbb{C}^{A_\bullet}$, its image contains an open dense subset. This proves the assertion that $Y_{A_\bullet} \to Y_{A_I} \to V_{A_\bullet}$ is a decomposition of covering spaces. We have already shown that each fiber of the map $Y_{A_\bullet} \to Y_{A_I}$ is a polynomial system with support $A_J$ with exactly $\MV(A_J)$ solutions. Thus when $1 < \MV(A_I) < \MV(A_\bullet)$, we have $\MV(A_J) > 1$, which shows that this decomposition is nontrivial. □

### 2.4. Computing the Decompositions.

We show how to compute the decompositions of $X_{A_\bullet} \to \mathbb{C}^{A_\bullet}$ from Section 2.3 when $A_\bullet$ is either lacunary or strictly triangular.

Let $A = \{0, \alpha_1, \ldots, \alpha_m\} \subset \mathbb{Z}^n$ be a collection of integer vectors. The sublattice $\mathbb{Z}A \subset \mathbb{Z}^n$ that it generates is the image of a $\mathbb{Z}$-linear map $\mathbb{Z}^m \to \mathbb{Z}^n$ and is represented by a $n \times m$ integer matrix $A$ whose columns are the vectors $a_i$. Suppose that $\mathbb{Z}A$ has rank $k$. A **Smith normal form** of $A$ is a factorization into integer matrices

$$ A = PDQ, $$

where $P \in \GL_n(\mathbb{Z})$ and $Q \in \GL_m(\mathbb{Z})$ are invertible, and $D$ is the rectangular matrix whose only nonzero entries are $d_1, \ldots, d_k$ along the diagonal of its principal $k \times k$ submatrix. These are the **invariant factors** of $A$ and they satisfy $d_1 | d_2 | d_3 | \cdots | d_k$.

The sublattice $\mathbb{Z}A \subset \mathbb{Z}^n$ has a basis given by the columns of the matrix $PD$. If we apply the coordinate change $P^{-1}$ to $\mathbb{Z}^n$, then $\mathbb{Z}A$ becomes the subset of the coordinate space $\mathbb{Z}^k \oplus 0^{n-k}$ given by $d_1 \mathbb{Z} \oplus d_2 \mathbb{Z} \oplus \cdots \oplus d_k \mathbb{Z} \oplus 0^{n-k}$.

Let us consider a Smith normal form (8) when $A$ is the collection of vectors in $A_\bullet$ and $\MV(A_\bullet) > 0$. Then $d_n > 0$ as $\mathbb{Z}A_\bullet$ has rank $n$, and $A_\bullet$ is lacunary when $d_n > 1$. In this
case, an identification \( \varphi : \mathbb{Z}^n \rightarrow \mathbb{Z}A \) is given by \( PD_n \), where \( D_n \) is the principal \( n \times n \) submatrix of \( D \). Recall from § 2.2 that the corresponding surjection \( \varphi^* : (\mathbb{C}^\times)^n \rightarrow (\mathbb{C}^\times)^n \) has kernel \( \text{Hom}(\mathbb{Z}^n/\mathbb{Z}A*, (\mathbb{C}^\times)^n) \). Let \( \psi := P^{-1} \). Then \( \psi \circ \varphi = D_n \), so that if we set \( \Psi := \psi^* \), then \( \Phi : (\mathbb{C}^\times)^n \rightarrow (\mathbb{C}^\times)^n \) is diagonal,

\[
\Phi \circ \Psi(x_1, \ldots, x_n) = (x_1^{d_1}, \ldots, x_n^{d_n}).
\]

Let \( y = (y_1, \ldots, y_n) \in (\mathbb{C}^\times)^n \). If we set \( \rho_i := |y_i| \) and \( \zeta_i := \arg(z_i) \) so that \( y_i = \rho_i e^{\sqrt{-1} \zeta_i} \), then \( (\Phi \circ \Psi)^{-1}(y) \) is the set

\[
\left\{ \left( \rho_1^{1/d_1} e^{\sqrt{-1} \theta_1}, \ldots, \rho_n^{1/d_n} e^{\sqrt{-1} \theta_n} \right) \bigg| \theta_i = \frac{\zeta_i + 2\pi j}{d_i} \quad \text{for} \quad j = 0, \ldots, d_i - 1 \right\}.
\]

Suppose that \( A_* \) is triangular, and let us use the notation of § 2.3.2. We suppose that \( I = [k] = \{1, \ldots, k\} \) and \( J = \{k+1, \ldots, n\} \). Given a polynomial \( f \) on \( (\mathbb{C}^\times)^n \), its restriction \( \overline{f} \) to a fiber of \( \Phi : (\mathbb{C}^\times)^n \rightarrow \mathbb{T}_I^k \) is a regular function on the fiber, which is isomorphic to \( \mathbb{T}_J \). To represent \( \overline{f} \) as a polynomial on \( \mathbb{T}_J \) depends on the choice of a point in that fiber. Indeed, suppose that \( f = \sum_{\alpha \in A} c_{\alpha} x^\alpha \). Let \( y \in \mathbb{T}_I^k \) and \( y_0 \in F^{-1}(y) \) be a point in the fiber above \( y \), so that \( \mathbb{T}_J \ni z \mapsto y_0 z \in F^{-1}(y) \) parameterizes \( F^{-1}(y) \). If we write \( \overline{\alpha} \) for the image of \( \alpha \in \mathbb{Z}^n \) in \( \mathbb{Z}_J = \mathbb{Z}_J^*/\mathbb{Z}_I^k \), then

\[
\overline{f}(z) = \sum_{\alpha \in A} c_{\alpha} (y_0 z)^\alpha = \sum_{\beta \in A} z^\beta \left( \sum_{\alpha \in \mathcal{A}_I} c_{\alpha} y_0^\alpha \right).
\]

A uniform choice of a point in each fiber is given by a splitting \( \mathbb{T}_I^k \rightarrow (\mathbb{C}^\times)^n \) of the map \( \Phi : (\mathbb{C}^\times)^n \rightarrow \mathbb{T}_I^k \). This gives an identification \( (\mathbb{C}^\times)^n = \mathbb{T}_I^k \times \mathbb{T}_J \). Then points \( y \in \mathbb{T}_I^k \) are canonical representatives of cosets of \( \mathbb{T}_J \). As \( k = [I] \), we may further fix isomorphisms \( \mathbb{T}_I^k \simeq (\mathbb{C}^\times)^k \) giving \( \mathbb{Z}_I^k \simeq \mathbb{Z}^k \) and \( \mathbb{T}_J \simeq (\mathbb{C}^\times)^{n-k} \) giving \( \mathbb{Z}_J \simeq \mathbb{Z}^{n-k} \).

Suppose now that \( A = A_I \), and we compute a decomposition (8). Since \( \mathbb{Z}A_I \) has rank \( k \), the diagonal matrix \( D \) has \( k \) nonzero invariant factors. The saturation \( L \) of \( \mathbb{Z}A_I \) is the image of \( PI_k \), where \( I_k \) is the \( n \times n \) matrix whose only nonzero entries are in its principal \( k \times k \) submatrix, which forms an identity matrix. Then \( \varphi = PI_k \) and \( \Phi = \varphi^* \). Applying the coordinate change \( \psi := P^{-1} \) to \( \mathbb{Z}^n \) identifies this saturation as the coordinate plane \( \mathbb{Z}^k \oplus 0^{n-k} \) and the lattice \( \mathbb{Z}A_I \) as \( d_1 \mathbb{Z} \oplus d_2 \mathbb{Z} \oplus \cdots \oplus d_k \mathbb{Z} \oplus 0^{n-k} \). As in Section 2.3.2 this identifies \( \mathbb{Z}/L \) with the complementary coordinate plane, \( 0^k \oplus \mathbb{Z}^{n-k} \). Setting \( \Psi := \psi^* \), the composition \( \Phi \circ \Psi \) is the projection to the first \( k \) coordinates,

\[
\Phi \circ \Psi : (\mathbb{C}^\times)^n \rightarrow (\mathbb{C}^\times)^k
\]

and we identify \( \mathbb{T}_J = \mathbb{1}^k \times (\mathbb{C}^\times)^{n-k} \) and \( \mathbb{T}_I^k = (\mathbb{C}^\times)^k \times 1^{n-k} \).

3. Algorithms for Solving Sparse Decomposable Systems

We describe algorithms for solving sparse decomposable systems, and suggest an application of these algorithms to computing a start system to solve general systems (not necessarily decomposable) of sparse polynomials. They are based on numerical homotopy continuation [20]. By “solve a system of polynomials”, we mean compute numerical approximations to the solutions which may then be refined using Newton iterations. The expected numbers of solutions to the systems we consider are mixed volumes as explained.
in the Bernstein-Kushnirenko Theorem. In principle, as the systems are square and we know the expected number of solutions, Smale’s $\alpha$-theory [24] enables approximations to solutions to be certified as approximate solutions in that Newton iterations converge quadratically to solutions, as explained in [13].

Let $A_\bullet$ be a collection of supports with $\text{MV}(A_\bullet) > 0$, so that $\pi: X_{A_\bullet} \rightarrow \mathbb{C}^{A_\bullet}$ is a branched cover and let $F \in \mathbb{C}^{A_\bullet}$. A start system $G$ for $A_\bullet$ is a pair $(G, \mathcal{V}(G))$ where $G \in \mathbb{C}^{A_\bullet}$ and $\mathcal{V}(G)$ consists of $\text{MV}(A_\bullet)$ distinct points. The convex combination of systems

$$H(t) = tF + (1-t)G \quad \text{for} \quad t \in \mathbb{C},$$

is a straight-line homotopy. Then $\mathcal{V}(H(t)) \subset (\mathbb{C}^x)^{A_\bullet} \times \mathbb{C}$ defines a curve $C$. Forgetting the $x$-coordinates gives a dominant map $C \rightarrow \mathbb{C}$. Restricting to points above $t \in [0,1]$ gives a family of arcs on $C$. Starting with the points of $\mathcal{V}(G)$ at $t = 0$, path-tracking along these arcs using $H(t)$ will give solutions to $\mathcal{V}(F)$ at $t = 1$ when $F$ is a regular value of $\pi$. This is an instance of a parameter homotopy [18, 21]. If $F$ is not a regular value but $\mathcal{V}(F)$ is still finite, then $\mathcal{V}(F)$ may be computed using endgames [2, 10].

3.1. Solving decomposable sparse systems. We describe algorithms that use Esterov’s conditions to solve a decomposable sparse polynomial system. In each, we let $\text{SOLVE}$ be an arbitrary algorithm for solving a polynomial system. We assume that the system $F$ to be solved is general given its support $A_\bullet$, and then use a parameter homotopy together with endgames to compute $\mathcal{V}(F)$.

Recall from Section 2.2 the relation between the linear map $\varphi = \Phi^*$ and the group homomorphism $\Phi = \varphi^*$. Furthermore, recall the identification in (4) for Algorithm 7 and the notation $F_\iota \in \mathbb{C}^{A_\iota}$ used in (7) for Algorithm 8.

Algorithm 7 (SolveLacunary).

**Input:** A general polynomial system $F$ whose support $A_\bullet$ is lacunary.

**Output:** All solutions $\mathcal{V}(F) \subset (\mathbb{C}^x)^n$.

**Do:**

1. **Compute a Smith normal form** (8) of $A_\bullet$, giving $\varphi = PD_n$, $\Phi = \varphi^*$, $\psi = P^{-1}$, and $\Psi = \psi^*$, so that $\Phi \circ \Psi$ is diagonal (9).
2. **Use $\text{SOLVE}$ to compute** $\mathcal{V}(\iota(F)) \subset (\mathbb{C}^x)^n$.
3. **Using the formula** (10) to compute $(\Phi \circ \Psi)^{-1}(y)$ for $y \in \mathcal{V}(\iota(F))$, return
   \[\{\Psi(w) \mid w \in \bigcup_{z \in \mathcal{V}(\iota(F))} (\Phi \circ \Psi)^{-1}(z)\}\].

**Proof of Correctness.** By Lemma 5 $\mathcal{V}(F) = \Phi^{-1}(\mathcal{V}(\iota(F)))$. We apply $\Psi$ to points of $(\Phi \circ \Psi)^{-1}(z)$ for $z \in \mathcal{V}(\iota(F))$ to obtain points of $\mathcal{V}(F)$ in their original coordinates. \qed

Algorithm 8 (SolveTriangular).

**Input:** A general polynomial system $F$ whose support $A_\bullet$ is triangular, witnessed by $0 < k < n$ such that $\text{rank}(\mathbb{Z}A_{[k]}) = k$.

**Output:** All solutions to $\mathcal{V}(F) \subset (\mathbb{C}^x)^n$. 
By Lemma 6, every solution \( F \) can be solved using \( \Phi \circ \Psi \), where \( \Phi = \varphi^* \) and \( \Psi = \psi^* \). We apply \( \xi \) to convert these points to the original coordinates.

Algorithm 9 (SolveDecomposable).

**Input:** A generic polynomial system \( F \) with support \( \mathcal{A}_* \).

**Output:** All solutions to \( \mathcal{V}(F) \subset (\mathbb{C}^*)^n \).

**Do:**

1. Compute a Smith normal form \( PDQ \) \([8]\) of \( \mathcal{A}_* \).
   - if \( d_n > 1 \), then return \( \text{SolveLacunary}(F) \).
   - if \( d_n = 1 \), then
     - for all \( \emptyset \neq I \subset [n] \) compute a Smith normal form \( PDQ \) \([8]\) of \( \mathcal{A}_I \).
   - if \( \text{rank}(D_I) = |I| \) for some \( I \), reorder so that \( I = [k] \) and return \( \text{SolveTriangular}(F, k) \).

2. else neither of Esterov’s conditions hold and return \( \text{BLACKBOX}(F) \).

**Proof of Correctness.** First note that if the algorithm halts, then it returns the solutions \( \mathcal{V}(F) \). Halting is clear in Case (3), but the other cases involve recursive calls back to Algorithm 9. In Case (1), SolveLacunary will call Algorithm 9 on a system \( \iota(F) \) whose mixed volume is less than \( \text{MV}(\mathcal{A}_*) \). In Case (2), SolveTriangular will call Algorithm 9 on systems \( F[k] \) and \( F_j \), each involving fewer variables than \( F \). Thus, in each recursive call back to Algorithm 9, either the mixed volume or the number of variables decreases, which proves that the algorithm halts.

3.2. Start Systems. The Bézout homotopy \([10]\) is a well-known parameter homotopy for solving a system \( F = (f_1, \ldots, f_n) \) where each \( f_i \) is a general polynomial of degree
$d_i$. In it, the start system is $G = (x_1^{d_1} - z_1, \ldots, x_n^{d_n} - z_n)$, and $\mathcal{V}(G) = \Phi^{-1}(z)$, where $\Phi$ is the diagonal map and $\Phi^{-1}(z)$ is determined by inspection from $\mathcal{V}(G)$. This start system is a highly decomposable sparse polynomial system consisting of supports which are subsets of the original support of $F$, but have the same mixed volume. We propose a generalization, in which Algorithm 9 is used to compute a start system.

**Example 10.** Suppose that we have supports $A_1 = A_2 = A$, which are given by the columns of the matrix $(0 0 1 1 2 3 3 3 4 5 5 6)$.

Then $\mathcal{V}(A_1, A_2) = \text{vol}(\text{conv}(A)) = 30$. Let $B_1 = B_2 = (0 0 3 3 6)$ be the set of vertices of $\text{conv}(A)$. Given a general system $F \in \mathbb{C}^A$, let $G \in \mathbb{C}^{B_1} \subset \mathbb{C}^A$ be obtained from $F$ by restriction to the monomials in $B$. (That is, we set coefficients of monomials $x^\alpha$ in $F$ to zero if $\alpha \notin B$.) Then $B_1$ is lacunary with the map $\Phi(x_1, x_2) = (x_1^3, x_2^2)$, and $\mathcal{V}(G)$ has five solutions. We may use Algorithm 9 (more specifically, Algorithm 7) to compute $\mathcal{V}(G)$, and then compute $\mathcal{V}(F)$ using the parameter homotopy

$$H(t) = tF + (1-t)G$$

with start system $G = H(0)$ and tracking from the solutions $\mathcal{V}(G)$ at $t = 0$.

Example 10 motivates our final algorithm. For a finite set $A \subset \mathbb{Z}^n$, let $v(A) \subset A$ be the subset of vertices of $\text{conv}(A)$. For a collection $A_\bullet = (A_1, \ldots, A_n)$ of supports, let $v(A_\bullet) := (v(A_1), \ldots, v(A_n))$. Note that if $G \in \mathbb{C}^{v(A_\bullet)}$ is a regular value of the branched cover $\pi|_{X_{v(A_\bullet)}} : X_{v(A_\bullet)} \to \mathbb{C}^{v(A_\bullet)}$ then $G$ is also a regular value of $\pi : X_{A_\bullet} \to \mathbb{C}^{A_\bullet}$. As such, $G$ may be taken as a start system for the parameter homotopy and may be used to compute $\mathcal{V}(F)$ for any $F \in \mathbb{C}^{A_\bullet}$ with $\mathcal{V}(F)$ finite. The benefit of this approach, as seen in Example 10, is that $\pi|_{X_{v(A_\bullet)}}$ is more likely than $\pi$ to be decomposable.

**Algorithm 11** (Decomposable Start System).

**Input:** A set $A_\bullet$ of supports.

**Output:** A start system $(G, \mathcal{V}(G))$ for $A_\bullet$.

**Do:**

1. Choose a general system $G \in \mathbb{C}^{v(A_\bullet)}$.
2. Compute $\mathcal{V}(G)$ using Algorithm 7.
3. Return the pair $(G, \mathcal{V}(G))$.

**Proof of Correctness.** As $G \in \mathbb{C}^{v(A_\bullet)}$ is general, it has $\mathcal{V}(v(A_\bullet))$ solutions. Since for each $i$, $\text{conv}(A_i) = \text{conv}(v(A_i))$, we have $\mathcal{V}(v(A_\bullet)) = \mathcal{V}(A_\bullet)$. Finally, $\mathbb{C}^{v(A_\bullet)}$ is the subspace of $\mathbb{C}^{A_\bullet}$ where the coefficients of non-extreme monomials in each polynomial are zero. Thus $G \in \mathbb{C}^{A_\bullet}$, which shows that $(G, \mathcal{V}(G))$ is a start system for $A_\bullet$. 

**Remark 12.** The Bézout homotopy motivated the idea behind Algorithm 11. However, if we apply Algorithm 11 to the system of supports $A_\bullet$, where $A_i$ is all monomials of
degree at most \( d_i \), then we will not get the start system for the Bézout homotopy. For example, when \( n = 2, d_1 = 2 \), and \( d_2 = 3 \), the supports are as shown.

Here, \( B_1 \) and \( B_2 \) are the supports of the start system for the Bézout homotopy.

We leave open the challenge of finding a simple, general method to replace each set \( A_i \) by a subset \( B_i \) of \( v(A_i) \), so that \( \text{MV}(A_*) = \text{MV}(B_*) \). A possible first step would be to refine the methods of \[5\]. This may lead to a simpler start system for a parameter homotopy to solve general systems with support \( A_* \).

\[ \diamond \]

4. A COMPUTATIONAL EXPERIMENT

We explored the computational cost of using Algorithm \[9\] to solve sparse decomposable systems, comparing timings to PHCPack \[28, 11\] on a family of related systems.

Let \( A_1 = (0 1 2 0 1), \ A_2 = (0 1 2 1 1), \ B_1 = (0 0 2 2), \) and \( B_2 = (0 1 2 0 2). \) We display these supports and their convex hulls below.

Let \( C := \{0, 1\}^5 \) be the vertices of the five-dimensional cube. We construct sparse decomposable systems from \( A_* := (A_1, A_2), \ B_* := (B_1, B_2), \) and \( C \) as follows.

Choose two injections \( i, j: \mathbb{Z}^2 \to \mathbb{Z}^5 \) such that \( i(\mathbb{Z}^2) \cap j(\mathbb{Z}^2) = \{0\} \). For example, choose four linearly independent vectors \( t_1, t_2, j_1, j_2 \in \mathbb{Z}^5 \), and define \( i(a, b) = a t_1 + b t_2 \), and the same for \( j \). Let us set

\[ A(i, j) := (i(A_1), i(A_2), j(B_1), j(B_2), C). \]

**Example 13.** We now illustrate Algorithm \[9\] in detail on \( A(i, j) \) by considering the case when \( t_1, t_2, j_1, j_2 \) are the first four standard unit vectors \( e_1, \ldots, e_4 \). Suppose \( F = (f_1, f_2, g_1, g_2, h) \) is a system of polynomials \( \mathbb{C}[x_1, x_2, y_1, y_2, z] \) with support \( A(e_1, e_2, e_3, e_4). \) We use superscripts to distinguish different calls of the same algorithm. When SolveDecomposable\(^{(1)}\)(\( F \)) is called, it first checks if \( F \) is lacunary (it is not as \( ZC = Z^5 \)), and then recognizes that \( F \) is triangular witnessed by \((f_1, f_2)\). As such, it calls SolveTriangular\(^{(1)}\)(\( F, 2 \)) which computes the \( \text{MV}(A_*) = 5 \) solutions \( p_1, \ldots, p_5 \) to \( V(f_1, f_2) \) with PHCPack, our choice of BLACKBOX.

As its penultimate task, SolveTriangular\(^{(1)}\) computes a fiber of the first solution \( p_1 \) by performing the substitution \((x_1, x_2) = p_1 \) in \( g_1, g_2 \) and \( h \), and recursively calls SolveDecomposable\(^{(2)}\) on the system \((g_1(p_1, y, z), g_2(p_1, y, z), h(p_1, y, z)) \in \mathbb{C}[y_1, y_2, z]. \) This system is recognized to be triangular witnessed by \((g_1, g_2)\) and SolveTriangular\(^{(2)}\)(\( g_1, g_2 \)) computes the \( \text{MV}(B_*) = 10 \) solutions \( q_1, \ldots, q_{10} \) using PHCPack. Next, SolveTriangular\(^{(2)}\)
computes a fiber above \( q_1 \) by performing the substitution \( y = (y_1, y_2) = q_1 \) in \( h(p_1, y, z) \) producing the univariate polynomial \( h(p_1, q_1, z) \) of degree 1 which has solution \((p_1, q_1, z_1)\). Finally, \( \text{SolveTriangular}^{(2)} \) performs a parameter homotopy from \( q_1 \) to \( q_i \) to populate the fibers above each \( q_i \). Thus \( \text{SolveTriangular}^{(1)} \) populates the fiber above \( p_1 \) consisting of \( 10 \cdot 1 = 10 \) solutions. As its final step, \( \text{SolveTriangular}^{(1)} \) uses parameter homotopies from \( p_1 \) to \( p_i \) to populate all fibers producing all \( 5 \cdot 10 = 50 \) solutions to \( \mathcal{V}(F) \).

The overhead of this algorithm includes computing Smith normal forms and the search for subsets witnessing triangularity. Additionally, it often requires more path-tracking than a direct use of PHCPack. Nonetheless, the overhead seems to be nominal, and compared to the paths tracked in PHCPack, the paths tracked in our algorithm either involve fewer variables or polynomials of smaller degree.

For example, in Example 13 our algorithm called PHCPack to solve two sparse polynomial systems with 5 and 10 solutions respectively. A parameter homotopy was called \( 10 - 1 = 9 \) times on a system with 1 solution, then a different parameter homotopy was called \( 5 - 1 = 4 \) times on a system with 10 solutions. In total, \( 5 + 10 + 9 + 40 = 64 \) individual paths were tracked. In contrast, a direct use of PHCPack involves tracking exactly \( \text{MV}(A(e_1, e_2, e_3, e_4)) = 50 \) paths, albeit in a higher dimensional space.

For more general \( i \) and \( j \), the recursive structure of our computation is similar to Example 13. Some notable differences include

1. \( i(A_s) \) or \( j(B_s) \) may be lacunary which induces further decompositions.
2. Monomial changes must be computed as \( i(A_s) \) or \( j(B_s) \) could involve all variables.
3. For most \( i, j \) the univariate polynomial obtained from \( h \) has degree 5 and is solved by computing eigenvalues of its companion matrix.

For example, if we choose \( e_1 - e_2, e_2 - e_3, e_3 - e_4, e_4 - e_5 \) for \( i_1, i_2, j_1, j_2 \), then again, no system in the algorithm is lacunary, but the univariate polynomial obtained from \( h \) has support \( \{0, 1, 2, 3, 4, 5\} \), so that \( \text{MV}(A(i, j)) = 250 \).

In our computational experiment, we produced 10962 instances of \( A(i, j) \) and solved each instance using our implementation of Algorithm 9 as well as with PHCPack. Due to ill-conditioning and heuristic choices of tolerances, some computations failed to produce all solutions. Such occurrences are not included in the data displayed below.

We give a scatter plot of the elapsed timings in Figure 1 with respect to the mixed volume of the system. Figure 2 displays box plots of the timings of each algorithm grouped by sizes of mixed volumes. The boxes range from the first quartile \( q_1 \) to the third quartile \( q_3 \) of the group data with whiskers extending to the smallest and largest data points which are not outliers. Outliers are the data points which are smaller than \( q_1 - 1.5I \) or larger than \( q_3 + 1.5I \) where \( I \) is the length of the interquartile range \( (q_1, q_3) \).

A more detailed account of these computations, along with our implementation in Macaulay2, may be found at the website for this paper.

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Figure 1. Scatter plot of timings

Figure 2. Box plot of timings
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