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Symbolic-Numeric Factorization of Differential Operators

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ABSTRACT

We present a symbolic-numeric Las Vegas algorithm for factoring Fuchsian ordinary differential operators with rational function coefficients. The new algorithm combines ideas of van Hoeij's "local-to-global" method and of the "analytic" approach proposed by van der Hoeven. It essentially reduces to the former in "easy" cases where the local-to-global method succeeds, and to an optimized variant of the latter in the "hardest" cases, while handling intermediate cases more efficiently than both.

CCS CONCEPTS

• **Computing methodologies** → **Hybrid symbolic-numeric methods**.

KEYWORDS

Linear differential equations, Monodromy, Rigorous numerics

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1 INTRODUCTION

Problem. Can numerical integration of differential equations help finding exact solutions? The present paper revisits one aspect of this question. To a linear ordinary differential equation

$$y^{(r)}(x) + a_{r-1}(x)y^{(r-1)}(x) + \cdots + a_0(x)y(x) = 0,$$

one classically associates the differential operator

$$L = \partial^r + a_{r-1}\partial^{r-1} + \cdots + a_1\partial + a_0,$$

where $\partial = \mathrm{d}/\mathrm{d}x$ is the standard derivation. Linear differential operators with coefficients $a_i \in \mathbb{K}(x)$ for some number field $\mathbb{K} \subset \mathbb{C}$ can be viewed as skew polynomials in ∂ over $\mathbb{K}(x)$, subject to the relation $\partial x = x\partial + 1$. They form a skew Euclidean ring which we denote by $\mathbb{K}(x)\langle\partial\rangle$.

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An operator L_1 is said to be a right-hand factor of $L \in \mathbb{K}(x)\langle\partial\rangle$ if there exists an operator L_2 such that $L = L_2L_1$; an operator with no proper right-hand factor is called irreducible. Factoring operators is helpful in understanding their solutions. More precisely, when $L = L_2L_1$, the solution space of L_1 is contained in that of L, whereas solutions w of L_2 give rise to solutions y of L via inhomogeneous equations of the form $L_1(y) = w$.

It is well-known that factorization in this setting is not unique. For instance, one has $\partial^2 = (\partial + 1/(x+\alpha))(\partial - 1/(x+\alpha))$ for any α, expressing that the solutions $y(x) = x + \alpha$ of all first-order equations $(x+\alpha)y'(x) = y(x)$ are gathered as solutions of $y''(x) = 0$.

In the present paper, we are interested in the problem of finding *one* factorization of an operator $L \in \mathbb{Q}(x)\langle\partial\rangle$ (or, more generally, $L \in \mathbb{K}(x)\langle\partial\rangle$) as a product $L = L_\ell \cdots L_1$ of irreducible operators $L_i \in \overline{\mathbb{Q}}(x)\langle\partial\rangle$. Since, once we have written $L = L_2L_1$, we can recursively try to factor L_1 and L_2, we will focus on the problem of finding any proper right-hand factor.

The problem of factoring differential operators can be rephrased using elementary differential Galois theory [22, 39]. The basic fact here is that the solution space V of the operator L is naturally equipped with an action of the *differential Galois group* G of L, and a subspace of V is the space of solutions of a right-hand factor if and only if it is invariant under this action. In other words, right-hand factors correspond bijectively to submodules of V viewed as module over $\mathbb{C}[G]$. This point of view allows one to study factorizations of differential operators using the general theory of modules over finite-dimensional associative algebras [*e.g.*, 24]. This is (explicitly or not) the philosophy of many of the algorithms for factoring operators or solving related problems.

Computing the differential Galois group is notoriously difficult [*e.g.*, 29]. However, as a linear algebraic group it admits a finite system of generators that can be described explicitly using values of analytic solutions of differential equations. This property suggests a symbolic-numeric approach to the factorization problem. The idea is to compute generators of the Galois group by solving the equations numerically, then search for a common invariant subspace and use it to reconstruct a candidate factor, and finally check one's guess by exact division.

Previous work. The standard general algorithm for factoring differential operators goes back to Beke [2] at the end of the 19th century, with modern improvements due to Schwarz [26], Bronstein [6] and Tsarev [30]. Beke's method and its modern variants reduce the problem of finding a right-hand factor of order k of L to that of finding a first-order right-hand factor of the kth exterior power of L, which they do by combining "local first-order factors" at each of the singular points of L. This strategy can be slow even in relatively simple cases for a number of reasons, including the size of exterior powers, the need to work over algebraic extensions of

the constants, and a possible combinatorial explosion in the recombination phase [31].

The only worst-case complexity bound we are aware of is due to Grigoriev [13], also using an improved variant of Beke's method. In the special case of a monic $L \in \mathbb{Q}[x]\langle\partial\rangle$ of order r and degree d, it states that L can be factored in time polynomial in $(\delta r d)^{r^4}$ where δ is the maximum degree of L_2 in any factorization $L = L_1 L_2 L_3$ with monic L_2, L_3. Grigoriev's worst-case bound for δ is more than doubly exponential in r (see Bostan *et al.* [3] for more on this).

More practical algorithms are based on two main ideas. One, the *eigenring method*, introduced by Singer [27] and improved by van Hoeij [33], applies mainly to operators that decompose as a least common left multiple of two right-hand factors. The other is a local-to-global approach due to van Hoeij [31]. It applies when the structure of local solutions at one of the singular points satisfies certain conditions, and leads in particular to an efficient algorithm for finding first-order factors. These two methods form the basis of the state-of-the-art implementation, due to van Hoeij [34] and available in Maple as `DEtools[DFactor]`. Beyond the case of first-order factors, though, they are incomplete and need to fall back on the exterior power method in "hard" cases (but still benefit from van Hoeij's fast algorithm for first-order factors then).

The symbolic-numeric approach to factorization outlined above was suggested by van der Hoeven, who also gave fast algorithms for the high-precision computation of generators of the Galois group with rigorous error bounds, and a heuristic method for "reconstructing" the group [35, 37]. Related symbolic-numeric methods have been developed for the problems of finding all first-order right-hand factors [17], and of computing Liouvillian solutions [20]. One of the present authors implemented van der Hoeven's approach and studied its practical behavior [12].

Once numeric approximations of the generators are available, the main task of the factorization algorithm is to find a non-trivial invariant subspace or prove that there is none. Van der Hoeven presents an algorithm for it in [35]. This task also appears as a basic problem in effective representation theory [*e.g.,* 21, Chap. 1]. Most of the literature in this area deals either with computations over finite fields or with issues specific to exact computations in characteristic zero. An exception is the early work of Gabriel [11]. We note also that Eberly [9, p. 245] suggested combining symbolic techniques with interval arithmetic for decomposing algebras and representations over number fields; however, no algorithm of this type appears to have been developed since then. Purely numerical methods for decomposing *unitary* representations [*e.g.,* 8] are a different subject with is own developments but are of limited relevance to our problem.

Leaving aside the issue of representing complex numbers in an algebraic algorithm, though, the case of complex representation is the simpler one. Speyer [28] explains how to compute invariant subspaces based on classical methods for decomposing finite-dimensional algebras [compare, *e.g.,* 5]. More generally, important ideas used in classical exact algorithms adapt to the rigorous numeric setting, including the Holt–Rees variant [15] of Norton's irreducibility test [23], and the use of splitting elements [9, 1].

Contribution. We present a new symbolic-numeric algorithm for factoring ordinary differential operators with rational function coefficients. We make two simplifying assumptions. Firstly, we restrict ourselves to *Fuchsian* operators, that is, operators with only regular singular points. This restriction makes some details of the description technically simpler, but we expect that a very similar approach works in general [*cf.* 35]. Secondly, we assume that the operator to be factored only admits a finite number of distinct factorizations. We say more on this assumption and how it could be lifted in Section 4 (see Footnote 1).

Our algorithm can be viewed as a hybrid of van Hoeij's and van der Hoeven's methods. We point out that van Hoeij's method for exponential parts of multiplicity one can be viewed as a special case of Norton's irreducibility test. This reinterpretation shows how it naturally applies to more instances in our symbolic-numeric setting. In the remaining cases, we fall back on the relevant part of van der Hoeven's method. As in van Hoeij's method, we make use of Hermite–Padé approximants in the reconstruction phase. We also propose several improvements that limit the need for very high numeric precision during reconstruction. Compared to van Hoeij's algorithm, the benefit of our method is that we do not resort to the exterior power method in any case. Compared to van der Hoeven's, our algorithm aims to conclude as often as possible without computing a complete set of generators of the group, saving on the most expensive part in practice.

An implementation is in progress, and first positive results of this hybrid algorithm are presented.

Outline. We first recall some background on the analytic theory of differential equations in Section 2. In Section 3, we specify the model of interval arithmetic used in our algorithms. In Section 4, we discuss the subproblem of reconstructing a factor from numerical initial conditions presumed to lie in a proper invariant subspace. Then, in Section 5, we present several criteria for finding such "seed vectors" or proving that no invariant subspace exists. The main algorithm, combining the tools from the previous two sections, appears in Section 6. Finally, in Section 7, we report on experiments with an implementation of the new algorithm.

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2 MONODROMY

The main points of the analytic theory of linear differential equations with rational coefficients that we will need are as follows. We refer to [14, 16, 22, 39] for more information.

Singular points. Let $L = \partial^r + a_{r-1}\partial^{r-1} + \cdots + a_0 \in \mathbb{K}(x)\langle\partial\rangle$ be a differential operator. Recall that the *singular points* of L are the poles of $a_0, \ldots, a_{r-1}$ in $\mathbb{P}^1(\mathbb{C})$; denote their set by Σ. Recall also that, on any simply connected domain $U \subset \mathbb{C}\backslash\Sigma$, the space of analytic solutions of the equation $L(y) = 0$ has dimension r. A point $x_0 \in \mathbb{P}^1(\mathbb{C})\backslash\Sigma$ that is not a singular point is called *ordinary*.

A point $\xi \in \Sigma$ is a *regular singular point* if the operator L_ξ obtained by making the change of variable $x \leftarrow \xi + z$ (resp. $x \leftarrow z^{-1}$ if $\xi = \infty$) in L has r linearly independent solutions $y_1, \ldots, y_r$, of

the form [25, Chap. V]

$$y_i(z) = z^{\alpha_i}(s_{i,d}(z)\log^d(z) + \cdots + s_{i,0}(z)) \tag{1}$$

for some $\alpha_i \in \overline{\mathbb{Q}}$, $d \in \mathbb{Z}_{\geqslant 0}$, and functions $s_{i,0}, \ldots, s_{i,d}$ analytic on a disk $|z| < \rho$. Thus the y_i are analytic on the slit disk $U = \{z : |z| < \rho,\ z \notin \mathbb{R}_{\leqslant 0}\}$. The α_i occurring in the basis (1) are called the *local exponents* at $x = \xi$ and are the roots of the *indicial polynomial* of L at ξ, a polynomial with coefficients in $\mathbb{K}(\xi)$ that is easily computed from the operator. (By *Fuchs' criterion*, $\xi \in \Sigma$ is a regular singular point if and only if, for $0 \leqslant k < r$, the valuation of a_k at ξ is at least $k - r$. Regularity can hence be checked syntactically.)

We assume from now on that all singular points of L are regular; an operator with this property is also called *Fuchsian*. Note that any factor of a Fuchsian operator is Fuchsian as well.

Right-hand factors and monodromy. Let $Y = (y_1, \ldots, y_r)$ be a basis of the solution space V of L on some simply connected domain $U \subset \mathbb{C}\backslash\Sigma$, and consider the associated *Picard–Vessiot extension*, that is, the differential field extension E of $\mathbb{C}(x)$ generated by the y_i. The *differential Galois group* of L can be defined as the group $\mathcal{G} = \mathrm{aut}_{\mathrm{diff}}(E/\mathbb{C}(x))$ of differential automorphisms of E whose restriction to $\mathbb{C}(x)$ is the identity. This is a linear algebraic group [22, Theorem 2.10]. The map ψ_Y sending each element $\mathcal{G}$ to the matrix in the basis Y of its action on V is a faithful representation. We denote its image by $\mathrm{Gal}(L, Y)$. For any ordinary point x_0, if Y is the unique basis whose Wronskian matrix $\mathrm{Wr}(y_1, \ldots, y_r)$ specializes to the identity matrix at $x = x_0$, then we also write $\mathrm{Gal}(L, x_0)$ in place of $\mathrm{Gal}(L, Y)$.

Solutions of L defined on U can be analytically continued along any path γ drawn in $\mathbb{C}\backslash\Sigma$; for fixed endpoints, the result depends only on the homotopy class of γ in $\mathbb{C}\backslash\Sigma$. The action M_γ of analytic continuation along a loop γ is an element of the differential Galois group. A (local) *monodromy matrix* of L around ξ in the basis Y is a matrix of the form $\psi_Y(M_\gamma)$ where γ is a loop starting from U and going around ξ once, in the positive direction, and enclosing no other singular point. While there can be several homotopy classes with this property, the *monodromy group in the basis* Y, that is, the matrix group generated by local monodromy matrices in the basis Y around each $\xi \in \Sigma$, is defined without ambiguity.

Proposition 2.1. *[39, Corollary 2.35] A subspace $V_1 \subset V$ is the space of solutions of a right-hand factor of L if and only if it is invariant under the action of the differential Galois group.*

Thus, for any solution f of L, the orbit $\mathbb{C}[\mathcal{G}]f$ is equal to the solution space of the *minimal annihilator* of f, that is, the monic operator R of least order such that $R(f) = 0$. The operator L is reducible if and only if V, viewed as a $\mathbb{C}[\mathcal{G}]$-module, admits a proper submodule. An operator is *decomposable* if it can be written as the least common left multiple (lclm) of operators of lower order, that is, if V is a direct sum of proper submodules.

Theorem 2.2 (Schlesinger). *[22, Theorem 2.28] The monodromy group of a Fuchsian operator is a Zariski-dense subset of the differential Galois group.*

Schlesinger's theorem reduces invariance under the differential Galois group to invariance under a finite number of matrices. A similar result holds in the irregular case as a consequence of Ramis' generalization of Schlesinger's theorem; see [35, Theorem 3].

Corollary 2.3. *A subspace $V_1 \subset V$ is the space of solutions of a right-hand factor $L_1 \in \mathbb{C}(x)\langle\partial\rangle$ of L if and only if it is left invariant by the monodromy matrices around all $\xi \in \Sigma$, or equivalently by any choice of all but one of them.*

Proof. Since $\mathcal{G}$ is an algebraic group, a subspace invariant under a Zariski-dense subset is invariant under it. The product of the local monodromy matrices is the identity, so $|\Sigma| - 1$ of them generate the same group as all of them, namely the monodromy group. □

Monodromy matrices typically have transcendental entries. Approximations with rigorous error bounds of the monodromy matrices can be computed using known algorithms for the rigorous numerical integrations of ODEs. The *formal monodromy matrix* at each $\xi \in \Sigma$, that is, the local monodromy matrix around ξ expressed in a suitable local basis of the type (1), though, can be computed exactly. (The computation essentially amounts to changing z^α into $e^{2\pi i\alpha}z^\alpha$ and $\log(z)$ into $\log(z) + 2\pi i$ in (1).) However, this is not enough to express the whole monodromy group in the same basis, as one has to do to get an effective version of Corollary 2.3.

Adjoints. Recall that the *adjoint* of an operator L is the image L^* of L by the anti-morphism of $\mathbb{K}(x)\langle\partial\rangle$ to itself mapping ∂ to $-\partial$.

Lemma 2.4. *Let C denote the companion matrix of L. Define the matrices $B_0, \ldots, B_{r-1}$ by $B_0 = I_r$ and $B_{k+1} = B_k' - B_kC^T$. Let P be the matrix whose $(k+1)$th row is the last row of B_k. Then the map $\varphi \mapsto P(x_0)(\varphi^{-1})^T P(x_0)^{-1}$ is a group isomorphism from $\mathrm{Gal}(L, x_0)$ to $\mathrm{Gal}(L^*, x_0)$.*

Proof. Let $W := \mathrm{Wr}(y_1, \ldots, y_r)$ where the y_i are solutions of L such that $W(x_0) = I_r$. Note that $W' = CW$. It can be proved [39, Exercise 2.30] that the matrix $U := (W^{-1})^T$ satisfies $U' = -C^TU$ and the last row $(v_1 \cdots v_r)$ of U is a basis of solutions of L^*. The B_k are defined so that $U^{(k)} = B_kU$. Let $V = \mathrm{Wr}(v_1, \ldots, v_r)$ and $Z = \mathrm{Wr}(z_1, \ldots, z_r)$ where the z_i are solutions of L^* such that $Z(x_0) = I_r$. Since $V = PU$ and $V = ZP(x_0)$, we have $\sigma(V)(x_0) = P(x_0)(\sigma(W)(x_0)^{-1})^T = \sigma(Z)(x_0)P(x_0)$ and therefore $\psi_Z(\sigma) = P(x_0)(\psi_Y(\sigma)^{-1})^T P(x_0)^{-1}$ for any $\sigma \in \mathcal{G}$. □

3 OPTIMISTIC ARITHMETIC

Our algorithms involve algebraic computations, including zero-tests, on complex numbers that are known only approximately (but can be recomputed to higher precision if necessary).

We formalize the way of performing these computations by the following variant of complex interval arithmetic. Complex numbers are replaced by exactly representable closed complex intervals, or *balls* [36], containing them. We denote by $\mathbb{C}_\bullet$ the set of balls. Given a ball $\boldsymbol{z} \in \mathbb{C}_\bullet$, we write $z \in \boldsymbol{z}$ to mean that z is a complex number contained in $\boldsymbol{z}$, and $\mathrm{rad}(\boldsymbol{z})$ to denote the radius of $\boldsymbol{z}$. We extend this notation to lists, vectors, matrices, and polynomials over $\mathbb{C}_\bullet$. A ball is *exact* when its radius is zero.

As with usual interval arithmetic, versions operating on balls of basic operations $* \in \{+, -, \times, /\}$ are defined so that $x * y \in \boldsymbol{x} * \boldsymbol{y}$ for all $x \in \boldsymbol{x}$, $y \in \boldsymbol{y}$, and we assume that $\mathrm{rad}(\boldsymbol{x} * \boldsymbol{y})$ tends to zero when

$\boldsymbol{x}$ tends to a point x_0 and $\boldsymbol{y}$ tends to a point y_0 (and both $(\boldsymbol{x}, \boldsymbol{y})$ and (x_0, y_0) are contained in the domain of continuity of $*$, *i.e.*, no division by zero occurs). However, the comparison $\boldsymbol{x} = \boldsymbol{y}$ returns "true" if and only if $\boldsymbol{x}$ and $\boldsymbol{y}$ intersect.

Thus, *when the working precision is large enough*, all tests involved in the execution of a particular algorithm on a given exact input yield the same outcome as they would in infinite precision, and the output is a rigorous enclosure of the exact result. At a smaller working precision, equality tests may incorrectly return "true", but we can still rigorously decide that two numbers are distinct provided that the control flow of their computation was not affected by previous incorrect tests. We call this model *optimistic arithmetic*. It is close to the one based on computable complex numbers used in [35], but more explicit about precision management.

Convention 3.1. We say that an algorithm satisfies some property *at high precision* when the property holds given an accurate enough input. More precisely, if $\boldsymbol{x}$ is the input of the algorithm, "at high precision, $P(x, \boldsymbol{x})$" means $\forall x, \exists \varepsilon, \forall \boldsymbol{x} \ni x,\ (\mathrm{rad}(\boldsymbol{x}) < \varepsilon \implies P(x, \boldsymbol{x}))$.

Roughly speaking, using optimistic arithmetic is legitimate in our context because (1) our irreducibility criteria are based on "open" conditions like checking that certain vectors span the whole ambient space, where the optimistic zero-test can do no worse than *underestimate* the dimension; (2) in the reducible case, candidate factors can be validated by an *a posteriori* divisibility check carried out in exact arithmetic.

More precisely, inspecting the behavior of key algebraic algorithms shows that they satisfy the following properties. The optimistic version can also fail when the algebraic analogue would not, typically by trying to divide by an interval containing zero. This manifests by an error that can be caught by the caller.

Lemma 3.2. *(Row echelon form.) Given $\boldsymbol{M} \in \mathbb{C}_\bullet^{m\times n}$, one can compute $\boldsymbol{R} \in \mathbb{C}_\bullet^{m\times n}$, $\boldsymbol{T} \in \mathbb{C}_\bullet^{n\times n}$ such that*

(1) $\boldsymbol{R}$ is row-reduced, in the sense that there is $0 \leqslant r \leqslant \min(m, n)$ and a list $j_0 < j_1 < \cdots < j_{r+1}$ where $j_0 = 0$ and $j_{r+1} = n + 1$, such that
- *for all $1 \leqslant i \leqslant r$, the j_ith column of $\boldsymbol{R}$ is exact, with the ith entry equal to one and all other entries equal to zero,*
- *for all $0 \leqslant i \leqslant r$ and $j_i < j < j_{i+1}$, each of the $m - i$ last entries of the jth column of $\boldsymbol{R}$ is a ball that contains zero,*

(2) r cannot exceed the rank of any $M \in \boldsymbol{M}$,
(3) for all $M \in \boldsymbol{M}$, there exist $R \in \boldsymbol{R}$ and an invertible $T \in \boldsymbol{T}$ such that $R = TM$,
(4) at high precision, r is equal to the rank of M and the reduced row echelon form of M belongs to $\boldsymbol{R}$.

In particular, at high precision, we can verify that an $M \in \mathbb{C}^{m\times n}$ has full rank.

Lemma 3.3. *(Kernel.) Given $\boldsymbol{M} \in \mathbb{C}_\bullet^{m\times n}$, one can compute $\boldsymbol{V} = (\boldsymbol{v}_1, \ldots, \boldsymbol{v}_\ell) \in \left(\mathbb{C}_\bullet^n\right)^\ell$ such that*

(1) any $v_1, \ldots, v_\ell$ with $v_i \in \boldsymbol{v}_i$ are linearly independent,
(2) for all $M \in \boldsymbol{M}$, there exists $V \in \boldsymbol{V}$, that is, $V = (v_1, \ldots, v_\ell)$ and $v_i \in \boldsymbol{v}_i$ for all i, such that $\ker(M) \subset \mathrm{span}(V)$,
(3) at high precision, the last inclusion is an equality.

In particular, at high precision, we can verify the nullity of a kernel.

Lemma 3.4. *(Spin-up.) Given a list $\boldsymbol{A} \in (\mathbb{C}_\bullet^{n\times n})^k$ of matrices and a vector $\boldsymbol{v} \in \mathbb{C}_\bullet^n$, one can compute $\boldsymbol{U} = (\boldsymbol{u}_1, \ldots, \boldsymbol{u}_\ell) \in \left(\mathbb{C}_\bullet^n\right)^\ell$ such that*

(1) any $u_1, \ldots, u_\ell$ with $u_i \in \boldsymbol{u}_i$ are linearly independent,
(2) for all $M \in \boldsymbol{A}$ and $v \in \boldsymbol{v}$, there exists $U \in \boldsymbol{U}$ such that $\mathbb{C}[A]v \supset \mathrm{span}(U)$,
(3) at high precision, the last inclusion is an equality.

In particular, at high precision, we can verify that $\mathbb{C}[A]v = \mathbb{C}^n$ when this is the case.

Lemma 3.5. *(Root isolation.) Given a monic polynomial $\boldsymbol{P}$, one can compute pairs $(\boldsymbol{\lambda}_1, m_1), \ldots, (\boldsymbol{\lambda}_\ell, m_\ell)$ such that*

(1) the $\boldsymbol{\lambda}_i \in \mathbb{C}_\bullet$ are pairwise disjoint and the m_i are positive,
(2) for all $P \in \boldsymbol{P}$, each $\boldsymbol{\lambda}_i$ contains exactly m_i roots (counted with multiplicities) of P, and all roots of P are contained in $\bigcup_i \boldsymbol{\lambda}_i$,
(3) at high precision, no two distinct roots of P are contained in the same λ_i.

In particular, at high precision, we can verify that a root is simple.

4 MINIMAL ANNIHILATORS

Like both van Hoeij's and van der Hoeven's, our factoring algorithm works by searching for a solution that belongs to a proper invariant subspace, and reconstructing an annihilator of that solution. In this section, we discuss the problem of reconstructing an invariant subspace, and a corresponding right-hand factor, from a seed vector.

We fix a monic differential operator $L \in \mathbb{K}(x)\langle\partial\rangle$ of order r, and an ordinary point $x_0 \in \mathbb{Q}$ of L. We denote $G = \mathrm{Gal}(L, x_0)$. A solution f of L is represented by the vector $v = (f(x_0), \ldots, f^{(r-1)}(x_0))^T$ (so that the action of $\mathcal{G}$ on f corresponds to a left action of G on v), and we sometimes abusively identify f with v.

We use Algorithm 1 to compute a right-hand factor of L from an approximate seed vector $\boldsymbol{v}$.

Proposition 4.1. *Fix $\varphi_0, \ldots, \varphi_k \in \mathbb{C}[G]$. Let $\boldsymbol{\varphi}_0, \ldots, \boldsymbol{\varphi}_k \in \mathbb{C}_\bullet^{r\times r}$ be such that $\varphi_i \in \boldsymbol{\varphi}_i$ for all i.*

(1) Annihilator(L, $\boldsymbol{v}$, $(\boldsymbol{\varphi}_0, \ldots, \boldsymbol{\varphi}_k)$, t) returns either the special value Inconclusive *or a right-hand factor $R \in \overline{\mathbb{Q}}(x)\langle\partial\rangle$ of L.*
(2) If the output is L, no $v \in \boldsymbol{v}$ admits an annihilator of order $< r$.

Assume further that exact initial conditions $v \in \mathbb{C}^r$ are fixed and $\boldsymbol{v}$ is chosen such that $\boldsymbol{v} \ni v$. Let M be the minimal annihilator of v.

(3) If $M \in \overline{\mathbb{Q}}(x)\langle\partial\rangle$, then, at high precision and for large enough t, the output is M.
(4) If $M = L$ and $\varphi_0, \ldots, \varphi_k$ generate $\mathbb{C}[G]$, the output at high precision is L with no assumption on t.

Proof. Assertion (1) is straightforward. If L is returned on line 2, the fact that no $v \in \boldsymbol{v}$ has an annihilator of smaller order is ensured by Lemma 3.4. Step 6 amounts to a kernel computation, so the same conclusion holds if the algorithm terminates on line 11, by Lemma 3.3. When termination happens on line 9, the returned R has order less than r. This proves (2). Let v and M be as in the statement and $V = \mathbb{C}[G]v$. Note that $L = M$ if and only if $V = \mathbb{C}^r$. At high precision, this is correctly decided on line 2 when $\mathbb{C}[\varphi_1, \ldots, \varphi_k] = \mathbb{C}[G]$ thanks to Lemma 3.4, proving (4). At high

precision, Lemma 3.3 ensures that, after line 6 is executed with $s = r - 1$, the resulting $\boldsymbol{R}$ contains an operator R of order at most $r - 1$ and minimum degree such that $R(f) = O((x - x_0)^t)$. When $M = L$, it follows that line 11 is eventually reached as $t \to \infty$. Assume now that $M \in \overline{\mathbb{Q}}(x)\langle\partial\rangle$ and $\operatorname{ord} M \neq L$. At high precision, by Lemma 3.2, step 1 yields a tuple $(\boldsymbol{e}_1, \dots, \boldsymbol{e}_d)$ with $d \leqslant \operatorname{ord} M$. Line 6 with $s = \operatorname{ord} M$ then finds an $\boldsymbol{R}$ with $M \in \boldsymbol{R}$. By assumption, M has coefficients in $\overline{\mathbb{Q}}$, so that the LLL algorithm eventually recovers M from $\boldsymbol{R}$ as the radii of the coefficients of $\boldsymbol{R}$ tend to zero. This proves (3). □

The assumption in Proposition 4.1*(3)* that the minimal annihilator of f has algebraic coefficients is automatically satisfied when L has a finite number of factorizations. Indeed, the (L_1, L_2) with $L = L_2 L_1$ form an algebraic variety defined over $\mathbb{K}$, which is then zero-dimensional. In the presence of parameterized families of right-hand factors (like in the example of ∂^2 mentioned in the Introduction), however, some choices of f lead to an annihilator with transcendental coefficients[1].

Remark 4.2. When $s = d$, a more direct approach for step 6 is to write $\boldsymbol{R}$ as a product of first-order factors with power series coefficients; see [38, Theorem 8] for a fast algorithm.

Remark 4.3. Due to interval blow-up, getting a precise enough $\boldsymbol{R}$ at step 6 to be able to proceed may require a large working precision. Instead, we can compute a minimal approximant basis of

$$(y_0, y_0', \dots, y_0^{(r-1)}, y_1, y_1', \dots, y_1^{(r-1)}, \dots, y_{r-1}, y_{r-1}', \dots, y_{r-1}^{(r-1)})$$

where $(y_0, \dots, y_{r-1})$ is the local basis (consisting of exact series) such that $\boldsymbol{f} = \boldsymbol{u}_0 y_0 + \cdots + \boldsymbol{u}_{r-1} y_{r-1}$. We then search for elements (of a certain maximum degree) of the form

$$(\boldsymbol{u}_0 q_0, \dots, \boldsymbol{u}_0 q_{r-1}, \boldsymbol{u}_1 q_0, \dots, \boldsymbol{u}_1 q_{r-1}, \dots, \boldsymbol{u}_{r-1} q_0, \dots, \boldsymbol{u}_{r-1} q_{r-1})$$

in the module of relations. The latter step reduces to solving a linear system over $\mathbb{C}_\bullet[x]$ given by a matrix mixing exact polynomials and constant ball entries [*cf.* 7].

Remark 4.4. Another way of limiting the need for Hermite–Padé approximants with high-precision ball coefficients is as follows. Between lines 2 and 3 of Algorithm 1, we insert a step that attempts to reconstruct a vector $e_1 \in \boldsymbol{e}_1 \cap \overline{\mathbb{Q}}^r$ using the LLL algorithm. If this succeeds, we compute the power series solution f_1 of L associated to e_1 and attempt to recover a factor from it. In the notation of Proposition 4.1, this strategy yields a proper factor at high precision when $\mathbb{C}[\varphi_0, \dots, \varphi_k] = \mathbb{C}[G]$. Indeed, $\boldsymbol{e}_1$ contains the first vector e_1 of the exact reduced echelon basis of V, and V is the image in $\mathbb{C}^r$ of the whole solution space of M. As M has coefficients in $\overline{\mathbb{Q}}(x)$, it admits a basis of solutions whose series expansions at x_0 have coefficients in $\overline{\mathbb{Q}}$. A solution g of M is represented in V by the vector $(g(x_0), \dots, g^{(r-1)}(x_0)) \in \overline{\mathbb{Q}}^r$, hence V is generated by vectors with entries in $\overline{\mathbb{Q}}$, and therefore the elements of its reduced echelon basis belong to $\overline{\mathbb{Q}}^r$ as well. (The resulting factor might not be an annihilator of f. This is easy to fix if desired.)

[1] The algorithm from [35] is incorrect as stated for this reason: when $\dim K_i > 1$ at step 5 of `Invariant_subspace`, the vector $\boldsymbol{v}$ chosen from K_i may correspond to a minimal annihilator with transcendental coefficients, in which case `Right_factor` will loop indefinitely. Van der Hoeven recently revised his algorithm to fix this issue (private communication).

[2] To reconstruct an element $z \in \overline{\mathbb{Q}}$ from a ball $\boldsymbol{z}$, we search for an algebraic number $z \in \boldsymbol{z} \cap \overline{\mathbb{Q}}$ of degree at most $\delta \sim (-\log(\operatorname{rad}(\boldsymbol{z})))^{1/2}$.

Algorithm 1: Annihilator(L, $\boldsymbol{v}$, $(\boldsymbol{\varphi}_0, \dots, \boldsymbol{\varphi}_k)$, t)

Input: $L \in \mathbb{K}(x)\langle\partial\rangle$ of order r, $\boldsymbol{v} \in \mathbb{C}_\bullet^r$, $\boldsymbol{\varphi}_0, \dots, \boldsymbol{\varphi}_k \in \mathbb{C}_\bullet^{r \times r}$, $t \in \mathbb{Z}_{>0}$

Output: a right-hand factor R of L, or *Inconclusive*

1 Compute the dimension d and a basis $(\boldsymbol{e}_1, \dots, \boldsymbol{e}_d) \in (\mathbb{C}_\bullet^r)^d$ of $\mathbb{C}[\boldsymbol{\varphi}_0, \dots, \boldsymbol{\varphi}_k]\boldsymbol{v}$ in reduced echelon form (Lemma 3.4);
2 if $d = r$ then return L;
3 Compute the first $t + r$ terms of the solution $\boldsymbol{f} \in \mathbb{C}_\bullet[[x - x_0]]$ of L defined by $(\boldsymbol{f}(x_0), \dots, \boldsymbol{f}^{(r-1)}(x_0))^T = \boldsymbol{v}$;
4 Compute B such that any monic right-hand factor of L has degree $\leqslant B$ [31, Section 9]; // precomputable
5 for $s = d, \dots, r - 1$:
6 Compute a monic $\boldsymbol{R} \in \mathbb{C}_\bullet(x)\langle\partial\rangle$ of minimum degree such that $\operatorname{ord} \boldsymbol{R} \leqslant s$ and $\boldsymbol{R}(\boldsymbol{f}) = O((x - x_0)^t)$ using Hermite–Padé approximation;
7 if $\deg \boldsymbol{R} < t/(s + 1)$ then
8 Compute $R \in \boldsymbol{R} \cap \overline{\mathbb{Q}}(x)\langle\partial\rangle$ using the LLL algorithm[2];
9 if R divides L from the right then return R;
10 if $\deg \boldsymbol{R} > B$ then // can only happen for large t
11 Return L;
12 Return *Inconclusive*;

Remark 4.5. If a right-hand factor of $L \in \mathbb{K}(x)\langle\partial\rangle$ has coefficients in $\mathbb{L}(x)$ for some extension $\mathbb{L}$ of $\mathbb{K}$, then its conjugates under the action of $\operatorname{Gal}(\mathbb{L}/\mathbb{K})$ are right-hand factors of L as well. Their lclm R is a right-hand factor with coefficients in $\mathbb{K}(x)$. As noted by van Hoeij [31, Section 8], if L is proved to be indecomposable, for instance because the eigenring method has failed to factor it, then R must be a proper factor. In the setting of Remark 4.4, this observation allows one to perform the Hermite–Padé step over $\mathbb{K}$ by replacing e_1 with the average of its Galois conjugates.

5 SUBMODULES AND IRREDUCIBILITY

Let L, x_0, and G be as in the previous section. We now discuss three different ways of finding proper invariant subspaces under the monodromy action (G-submodules) or proving that none exists.

All three tests follow the same pattern. We start with a possibly incomplete set of (approximate or exact) generators of the monodromy group. When one of the tests is applicable, either we exploit error bounds to certify the absence of any proper submodule, which implies that L is irreducible, or we find an approximation $\boldsymbol{v}$ of a candidate v such that $\mathbb{C}[G]v \subsetneq \mathbb{C}^r$, from which we attempt to reconstruct a factor of L by Algorithm 1.

Let $\mathcal{A} \subset \mathbb{C}^{r \times r}$ be a matrix algebra. In our applications, $\mathcal{A}$ will be the algebra $\mathbb{C}[G]$ considered in the previous section or a subalgebra of it. We will consider both the left action of $\mathcal{A}$ on the column space $\mathbb{C}^{r \times 1}$ and the right action of $\mathcal{A}$ on the row space $\mathbb{C}^{1 \times r}$. If nothing is specified, $\mathbb{C}^r$ stands for the left $\mathcal{A}$-module $\mathbb{C}^{r \times 1}$.

Algorithm 2: SimpleEigenvalue(L, $(\boldsymbol{\varphi}_0, \ldots, \boldsymbol{\varphi}_k)$, t)

Input: $L \in \mathbb{K}(x)\langle\partial\rangle$ of order r, $\boldsymbol{\varphi}_0, \ldots, \boldsymbol{\varphi}_k \in \mathbb{C}_\bullet^{r\times r}$, $t \in \mathbb{Z}_{>0}$
Output: a right-hand factor of L, *Irreducible*, or *Inconclusive*

1 Compute a simple eigenvalue $\boldsymbol{\lambda}$ of $\boldsymbol{\varphi}_0$ and an eigenvector $\boldsymbol{v}$ of $\boldsymbol{\varphi}_0$ associated to $\boldsymbol{\lambda}$; // may fail
2 R = Annihilator(L, $\boldsymbol{v}$, $(\boldsymbol{\varphi}_0, \ldots, \boldsymbol{\varphi}_k)$, t);
3 if $\mathrm{ord}(R) < \mathrm{ord}(L)$ then return R;
4 Compute $P(x_0)$ as in Lemma 2.4; // precomputable
5 Compute $\boldsymbol{\chi}_0, \ldots, \boldsymbol{\chi}_k$ for $\chi_i := P(x_0)\varphi_i^T P(x_0)^{-1}$, $0 \leqslant i \leqslant k$;
6 Compute an eigenvector $\boldsymbol{w}$ of $\boldsymbol{\chi}_0$ associated to $\boldsymbol{\lambda}$; // may fail
7 Q = Annihilator(L^*, $\boldsymbol{w}$, $(\boldsymbol{\chi}_0, \ldots, \boldsymbol{\chi}_k)$, t);
8 if $\mathrm{ord}(Q) < \mathrm{ord}(L)$ then return $(L^*/Q)^*$;
9 else if $R = L$ and $Q = L^*$ then return *Irreducible*;
10 else return *Inconclusive*; // R or Q is *Inconclusive*

It is classical [19] that the $\mathcal{A}$-module $\mathbb{C}^r$ admits a proper submodule if and only if $\mathcal{A} \neq \mathbb{C}^{r\times r}$. Note that this criterion provides no proper $\mathcal{A}$-submodule, even if one exists.

Norton's criterion. The following result is a special case of Norton's irreducibility test, in the form used in the Holt–Rees variant of the "Meataxe" algorithm for testing the irreducibility of modules over finite fields [15]. (The general case, allowing for an eigenvalue of multiplicity > 1, is not usable over an infinite field.)

Proposition 5.1. *[23, 15] Assume that there is $M \in \mathcal{A}$ having a simple eigenvalue λ. Introduce nonzero vectors $v \in \mathbb{C}^{r\times 1}$ and $w \in \mathbb{C}^{1\times r}$ such that $Mv = \lambda v$ and $wM = \lambda w$. Then, equivalently: (i) the left $\mathcal{A}$-module $\mathbb{C}^{r\times 1}$ is irreducible; (ii) both $\mathcal{A}v = \mathbb{C}^{r\times 1}$ and $w\mathcal{A} = \mathbb{C}^{1\times r}$ hold; (iii) the right $\mathcal{A}$-module $\mathbb{C}^{1\times r}$ is irreducible.*

Proof. For $w \in \mathbb{C}^{1\times r}$ and $v \in \mathbb{C}^{r\times 1}$, write $\langle w, v\rangle$ for $\sum_{i=1}^r w_i v_i$. For a subspace $F \subset \mathbb{C}^{r\times 1}$, we denote by $F^\perp := \{w \in \mathbb{C}^{1\times r} \mid \forall u \in F, \langle w, u\rangle = 0\}$ the orthogonal of F. We define symmetrically the orthogonal $G^\perp$ of a subspace $G \subset \mathbb{C}^{1\times r}$. For any subspace $F \subset \mathbb{C}^{r\times 1}$, $F = F^{\perp\perp}$ holds and F is a left $\mathcal{A}$-module if and only $F^\perp$ is a right $\mathcal{A}$-module; similarly for subspaces $G \subset \mathbb{C}^{1\times r}$.

Assume (ii) does not hold. If $0 \subsetneq w\mathcal{A} \subsetneq \mathbb{C}^{1\times r}$, then $\mathbb{C}^{r\times 1} \supsetneq (w\mathcal{A})^\perp \supsetneq 0$, and $(w\mathcal{A})^\perp$ is a proper submodule of $\mathbb{C}^{r\times 1}$. Otherwise, $0 \neq \mathcal{A}v \neq \mathbb{C}^{r\times 1}$, making $\mathcal{A}v$ a proper submodule. So $\mathbb{C}^{r\times 1}$ is a reducible module in all cases.

Conversely, assume (i) does not hold, and let U be a proper $\mathcal{A}$-submodule of $\mathbb{C}^{r\times 1}$. The equality $\ker(M-\lambda I_r) = \mathcal{A}v$ holds because λ is a simple eigenvalue. If $\mathcal{A}v \subset U$, then $\mathcal{A}v \neq \mathbb{C}^{r\times 1}$. Otherwise, $\ker(M - \lambda I_r) \cap U = \{0\}$. Since $(M - \lambda I_r)U \subset U$, we have $(M - \lambda I_r)U = U$ by finite dimension. Hence, for all $u \in U$, there is $u' \in U$ such that $\langle w, u\rangle = \langle w, (M-\lambda I_r)u'\rangle = \langle w(M-\lambda I_r), u'\rangle = \langle 0, u'\rangle = 0$. Therefore $w \in U^\perp$, so $w\mathcal{A} \subset U^\perp$ and $w\mathcal{A} \neq \mathbb{C}^{1\times r}$. □

In the special case where M is a formal monodromy matrix, we recover van Hoeij's local-to-global method. Indeed, at a regular singular point, the *exponential parts* defined in [31, Section 3] correspond to the eigenvalues of the formal monodromy matrix. Van Hoeij observes that one can find a factorization or prove that there is none as soon as there is an exponential part e of multiplicity 1 at some singular point, because e is then an exponential part of either L_1 or L_2 but not both in a factorization $L = L_2L_1$. To decide whether e is an exponential part of a right-hand factor, van Hoeij computes a series solution f associated to e and searches for an annihilator of f of order smaller than r using Hermite–Padé approximants. Thanks to degree bounds, it is possible to ensure that e is not an exponential part of any right-hand factor. As noted in Section 2, this is equivalent to $\mathbb{C}[G]f$ being $\mathbb{C}^r$. One can decide if e is an exponential part of a left-hand factor in a similar way, by passing to the adjoint operator.

In the setting where $\mathcal{A} = \mathbb{C}[G]$, we can test point (ii) of Proposition 5.1 in two different ways: we either compute bases of $\mathcal{A}v$ and $w\mathcal{A}$ by saturation, or search for annihilators satisfying certain degree bounds as in van Hoeij's method. The first method is typically more efficient when a full basis of $\mathcal{A}$ is available, but the second has the advantage of being applicable even if only part of the monodromy matrices have been computed. Compared to van Hoeij's method, the numerical test applies to a larger class of operators because an element of $\mathcal{A}$ can have a simple eigenvalue even if the generators only have multiple eigenvalues.

As we will now show, performing either variant of this test using optimistic arithmetic can prove irreducibility, or provide a candidate invariant subspace, depending on the reducibility of the operator.

Proposition 5.2. *Suppose that L is a monic Fuchsian operator admitting finitely many distinct right-hand factors. Fix $\varphi_0, \ldots, \varphi_k \in \mathbb{C}[G]$ and let R be the output of* SimpleEigenvalue$(L, (\boldsymbol{\varphi}_0, \ldots, \boldsymbol{\varphi}_k), t)$ *where $\varphi_i \in \boldsymbol{\varphi}_i$. If $R =$* Irreducible*, then L is irreducible. If R is an operator, then R is a proper right-hand factor of L. Assume further that φ_0 has a simple eigenvalue. Then, at high precision: (1) R is either a factor or* Irreducible *for large t; (2) if L is irreducible and the φ_i generate $\mathbb{C}[G]$, the output is* Irreducible.

Proof. Assume that the computation of the eigenvalues of $\boldsymbol{\varphi}_0$ finds an eigenvalue $\boldsymbol{\lambda}$ of multiplicity 1. Lemma 3.5 ensures that φ_0 admits a simple eigenvalue $\lambda \in \boldsymbol{\lambda}$, and, by Lemma 3.3, the eigenvectors v of φ_0, w of χ_0 for λ belong to the respective computed eigenvectors $\boldsymbol{v}$ of $\boldsymbol{\varphi}_0$, $\boldsymbol{w}$ of $\boldsymbol{\chi}_0$ for $\boldsymbol{\lambda}$. By Proposition 4.1, the call to Annihilator on line 2 (if it succeeds) either yields a proper factor or proves that the minimal annihilator of v is L. Since the group generated by the φ_i is the same as the one generated by the φ_i^{-1}, the χ_i are elements of $\mathbb{C}[\mathrm{Gal}(L^*, x_0)]$ by Lemma 2.4, so a similar reasoning applies to line 7. If the minimal annihilators turn out to be L and L^*, then point (ii) of Proposition 5.1 holds with $\mathcal{A} = \mathbb{C}[\varphi_0, \ldots, \varphi_k]$, hence also with $\mathcal{A} = \mathbb{C}[G]$, and we can conclude that L is irreducible. Finally, at high precision, when φ_0 does have a simple eigenvalue, all numerical steps succeed, and assertions (1)–(2) follow from assertions (3)–(4) in Proposition 4.1. □

One-dimensional eigenspaces. It is not unusual in applications to encounter operators whose local monodromy matrices have a single eigenvalue, yet with a one-dimensional eigenspace ("MUM points"). The following test is useful in particular for dealing with combinations of such operators. As Norton's criterion adapts to van Hoeij's method, so too does this next test sometimes apply to a formal monodromy matrix. It could therefore also be used in a purely symbolic factoring algorithm.

Proposition 5.3. *Assume that there is $M \in \mathcal{A}$ whose eigenspaces $E_1, \dots, E_\ell$ are all 1-dimensional. Let $v_i \in \mathbb{C}^r$ satisfy $E_i = \mathbb{C}v_i$ for each $1 \leqslant i \leqslant \ell$. Then $\mathbb{C}^r$ is an irreducible $\mathcal{A}$-module if and only if $\mathcal{A}v_i = \mathbb{C}^r$ for all $1 \leqslant i \leqslant \ell$.*

Proof. The eigenvalues of the restriction of M to an invariant subspace are eigenvalues of M, so any nonzero invariant subspace must intersect at least one eigenspace of M in a nontrivial way. □

Let us explain why this test can again prove the irreducibility at high precision. We denote by $\boldsymbol{\lambda}_1, \dots, \boldsymbol{\lambda}_\ell$ the eigenvalues of a ball approximation $\boldsymbol{M}$ of an element $M \in \mathcal{A}$, and we assume that, for each $1 \leqslant i \leqslant \ell$: (1) the optimistic computation of $\ker(\boldsymbol{M} - \boldsymbol{\lambda}_i I_r)$ returns a single vector $\boldsymbol{v}_i$, and (2) the optimistic computation of the orbit of $\boldsymbol{v}_i$ returns r independent vectors. Then all the eigenspaces of M are 1-dimensional and one has $\mathcal{A}v = \mathbb{C}^r$ for each eigenvector v of M. Indeed, consider an eigenvalue μ of M. Since $\mu \in \boldsymbol{\lambda}_i$ for some i, there exists $v \in \boldsymbol{v}_i$ such that $\ker(M - \mu I_r) \subset \mathbb{C}v$. But $\ker(M - \mu I_r) \neq \{0\}$ so $\ker(M - \mu I_r) = \mathbb{C}v$. Next, $\mathcal{A}v = \mathbb{C}^r$ thanks to the computation of the orbit of $\boldsymbol{v}_i$. Note that all the distinct eigenvalues of M do not need to be isolated in different $\boldsymbol{\lambda}_i$.

This leads to a procedure OneDimEigenspaces, which we omit, with similar correctness properties as SimpleEigenvalue.

Van der Hoeven's algorithm revisited. The following result is based on the ideas introduced in [35]. It allows us to deal with the cases that cannot be handled by the two previous criteria.

Proposition 5.4. *Assume that all the matrices of $\mathcal{A}$ have at least one multiple eigenvalue. Consider $M \in \mathcal{A}$ with a maximal number of eigenvalues. Denote by λ one of its multiple eigenvalues, by E the generalized eigenspace of M for λ, that is, $E = \ker((M - \lambda I_r)^r)$, and by F the sum of the other generalized eigenspaces of M, so that $\mathbb{C}^r = E \oplus F$. Let $K := \{v \in E \mid \forall N \in \mathcal{A}, PNv \in \mathbb{C}v\}$ where $P \in \mathcal{A}$ denotes the projection onto E along F.*

Then $K \neq \{0\}$ and $\mathcal{A}v$ is a proper $\mathcal{A}$-submodule of $\mathbb{C}^r$ for any nonzero $v \in K$. In particular, the $\mathcal{A}$-module $\mathbb{C}^r$ is reducible.

Proof. Let $N \in \mathcal{A}$ and φ be the endomorphism of E defined by $\varphi(v) := PNv$. Note that $PNv = PNPv$ for any $v \in E$. Let us show that φ has a unique eigenvalue. Otherwise, take a nonzero eigenvalue μ of φ. Hence μ is also an eigenvalue of $PNP \in \mathcal{A}$. Denote by E_μ the generalized eigenspace of PNP for μ, by G the sum of the other generalized eigenspaces of PNP and by Q the projector onto E_μ along G. It is then classical [4, A.VII.31, Prop. 3] that the projector P, respectively Q, can be written as a polynomial in M, respectively in PNP, so P and Q belong to $\mathcal{A}$. Hence QP is the projector onto $E \cap E_\mu$ along $(E \cap G) \oplus F$. Since $E \cap E_\mu \subsetneq E$, we observe that $M + \alpha QP$ has more eigenvalues than M for any α such that $\lambda + \alpha$ is not an eigenvalue of M; this is in contradiction with the assumption made on M.

Define $\mathcal{A}_E := \{\varphi_N - \lambda_N \operatorname{id}_E ; N \in \mathcal{A}\}$, where φ_N is the endomorphism of E defined by $\varphi_N(v) := PNv$ and λ_N is its unique eigenvalue, so that $K = \bigcap_{n \in \mathcal{A}_E} \ker(n)$. Owing to a result of Levitski [18, Theorem 35, p. 135] that states that a semigroup of nilpotent endomorphisms is simultaneously triangularizable, showing $K \neq \{0\}$ reduces to showing that $\mathcal{A}_E$ is stable by composition. For all $N, R \in \mathcal{A}$, we have $(\varphi_N - \lambda_N \operatorname{id}_E)(\varphi_R - \lambda_R \operatorname{id}_E) = \varphi_S + \lambda_N \lambda_R \operatorname{id}_E$ where $S := NPR - \lambda_N R - \lambda_R N \in \mathcal{A}$. Applying the equality of endomorphisms to any nonzero eigenvector v of φ_R shows $\lambda_S = -\lambda_N \lambda_R$.

For the statement on $\mathcal{A}v$, we proceed by contraposition. If $v \in K$ satisfies $\mathcal{A}v = \mathbb{C}^r$, there is $N \in \mathcal{A}$ such that $Nv \in E \backslash \mathbb{C}v$ because the dimension of E is at least 2, so $v \notin K$. □

Algorithm 3: RightFactor(L)

Input: $L \in \mathbb{K}(x)\langle\partial\rangle$ of order r
Output: a proper right-hand factor R of L or *Irreducible*

```
Choose an ordinary base point x_0 ∈ ℚ;
Compute the finite singular points ξ_1, ..., ξ_ν of L;
Set some initial working precision p and truncation order t;
try:
    for i = 1, ..., ν:
        Compute an enclosure φ_i ∈ ℂ^{r×r}_• of a monodromy
          matrix around ξ_i, working at prec. p;    // may fail
        φ = a random combination of φ_1, ..., φ_i;
        if φ has a simple eigenvalue then
            R = SimpleEigenvalue(L, (φ, φ_1, ..., φ_i), t);
        else if all eigenspaces of φ are 1-dimensional then
            R = OneDimEigenspaces(L, (φ, φ_1, ..., φ_i), t);
        else
            R = MultipleEigenvalue(L, (φ, φ_1, ..., φ_i), t);
        if R ≠ Inconclusive then return R;
catch: Failure      // e.g., division by 0 in a basic subroutine
    Increase p and go to line 4;
Increase t and p and go to line 4;
```

This proposition also implies an irreducibility criterion ("if some $M \in \mathcal{A}$ has only simple eigenvalues and $\mathcal{A}v = \mathbb{C}^r$ for each v in a basis of eigenvectors, then $\mathbb{C}^r$ is irreducible"), but this criterion is weaker than Norton's. Again we omit the corresponding procedure MultipleEigenvalue, which computes the space K of Proposition 5.4, then calls Annihilator (Algorithm 1) on any of its nonzero elements. Since K can be written as an intersection of kernels, the convergence of its computation at high precision is ensured by Lemma 3.3.

Proposition 5.5. *Suppose that L is a monic Fuchsian operator admitting finitely many distinct right-hand factors. Fix $\varphi_0, \dots, \varphi_k \in \mathbb{C}[G]$ and let $R =$* MultipleEigenvalue$(L, (\boldsymbol{\varphi}_0, \dots, \boldsymbol{\varphi}_k), t)$ *where $\varphi_i \in \boldsymbol{\varphi}_i$. Then R is either the special value* Inconclusive *or a proper right-hand factor of L. Assume additionally that L is reducible and that φ_0 has a maximal number of eigenvalues among the elements of $\mathbb{C}[G]$. Then, at high precision, if $\varphi_0, \dots, \varphi_k$ generate $\mathbb{C}[G]$ and t is large enough, the algorithm neither fails nor returns* Inconclusive.

6 FACTORING

The three previous tests combine into a factorization procedure described in Algorithm 3. Since no bounds for a sufficient numeric precision are known, the strategy consists in increasing the precision p every time it turns out to be insufficient until getting either a proper factor or an irreducibility certificate.

Bounds on the possible degrees of right-hand factors exist, but these bounds can be large even when the operator is irreducible.

We hence increase also the series truncation order t progressively, in the hope of proving irreducibility by purely numerical methods ($t \approx 0$) or finding factors of low degree ($t \gtrsim \deg(L)\operatorname{ord}(L)$) before reaching the bound. Increasing t requires increasing p as well, to compensate for both loss of precision in larger computations and the expected larger bit-size of coefficients of high-degree factors.

Computing monodromy matrices (though asymptotically of cost softly linear in p) is by far the most expensive step in practice; therefore, for given p and t, we try to use as few of them as possible.

Line 7 of Algorithm 3 needs additional explanations. The idea is that taking a random element of $\mathbb{C}[\varphi_1, \dots, \varphi_i]$ will immediately provide a φ satisfying the assumptions of Proposition 5.1 or Proposition 5.4. This is made precise in the following result. In practice, rather than maintaining a basis of $U = \mathbb{C}[\varphi_1, \dots, \varphi_i]$, we can multiply together a few linear combinations of $\varphi_1, \dots, \varphi_i$, increasing that number if necessary. At worst, multiplying $\dim U$ random linear combinations of generators will yield a "generic" element.

Lemma 6.1. *[10, Lemma 2.1]. Let $U \subset \mathbb{C}^{r\times r}$ be a vector space. Let m be the maximum cardinality of the spectrum of any element of U. The elements of U with less than m distinct eigenvalues form a proper algebraic subset of U.*

Another subtlety is that the increase of p on line 17 is important to ensure termination: without it the working precision might not suffice to compensate for the additional work due to a larger t, and interval computations could fail at every iteration.

Proposition 6.2. *Let $L \in \mathbb{K}(x)\langle\partial\rangle$ be a Fuchsian operator. Assume that L admits a finite number of factorizations as a product of irreducible elements of $\overline{\mathbb{Q}}(x)\langle\partial\rangle$. There exists a proper algebraic subset $X \subsetneq \mathrm{Gal}(L, x_0)$ such that Algorithm 3 terminates provided that $\boldsymbol{\varphi} \cap X = \varnothing$ at step 7 of every iteration. Algorithm 3 then returns* Irreducible *if and only if L is irreducible, and returns a proper right-hand factor of L otherwise.*

Heuristically, when L is irreducible, we expect the algorithm to conclude as soon as $\mathbb{C}[\varphi_1, \dots, \varphi_i]$ contains a matrix with a simple eigenvalue and enough other elements of $\mathbb{C}[G]$ that Norton's test passes. Verifying irreducibility this way should require only a moderate p and does not depend on t. In the reducible case, t and p need to reach the total arithmetic size, resp. the bit size of the coefficients, of at least one right-hand factor before the computation has any chance of finishing. Once t and p are large enough, we can expect again the computation to finish as soon as $\mathbb{C}[\varphi_1, \dots, \varphi_i]$ contains a matrix to which either SimpleEigenvalue or OneDimEigenspaces applies[3]. MultipleEigenvalue, in contrast, provides no guarantee of finding a factor before the last iteration, but may still do so in a number of situations involving left-hand factors of low order.

The version presented here is but a simple illustration of how the tests described above can be combined, and many improvements are possible in practice. First of all, at the price of minor technical complications, we can take x_0 to be a well-chosen singular point and $\xi_1 = x_0$. The first iteration of the loop on i then require no numerical monodromy computation and parts of it can be performed in exact arithmetic if desired, essentially reducing to van Hoeij's method. Like in the exact case [31, Section 8], it may be worth trying the eigenring method before using Algorithm 3. Obviously, one should compute information such as degree bounds only once, and, when computing a complete factorization, reuse the monodromy matrices from the caller in recursive calls. Finally, one needs reasonable heuristics to decide how to increase p and t and skip some steps which one expects to fail or to be too costly.

[3]This holds true also in the irreducible case if t is large not only compared to the degrees of actual factors but compared to van Hoeij's bound.

7 EXPERIMENTAL RESULTS

We are working on an implementation of Algorithm 3 in SageMath. Our code is available in an experimental branch of the ore_algebra package[4], under the GNU GPL. It currently implements none of the tricks described outside the pseudo-code blocks, except for the technique of Remark 4.4, which in fact completely replaces lines 5–9 of Algorithm 1, so that irreducibility results are based on monodromy matrices only.

To extensively test our implementation, we developed a generator of random Fuchsian operators, following the theory in [16, §15.4]. After fixing the order r and singularities $\Sigma = \{\xi_1, \dots, \xi_\nu, \infty\}$, the coefficients of a Fuchsian operator $L = \partial^r + \sum_{m=1}^{r} p_m(x)\partial^{r-m}$ can always be written in the form

$$p_m(x) = \sum_{s=1}^{\nu} \frac{P_{m,s}}{(x-\xi_s)^m} + \frac{A_m x^{m\nu-m-\nu} + O(x^{m\nu-m-\nu-1})}{(x-\xi_s)^{m-1}} \qquad (2)$$

for constants $P_{m,s}$ and A_m with $A_1 = 0$. Those constants depend polynomially on the local exponents $\alpha_{\xi,1}, \dots, \alpha_{\xi,r}$ at each $\xi \in \Sigma$. We choose the $\alpha_{\xi,k}$ as random rational numbers satisfying the Fuchs relation $\sum_{\xi,k} \alpha_{\xi,k} = \frac{1}{2}r(r-1)(\nu-1)$. Any such choice provides coefficients $P_{m,s}$ and A_m, while the $\frac{1}{2}(r-1)(r\nu-r-2)$ coefficients hidden under the $O(\cdot)$ can be taken as independent random rational numbers. Generically, the resulting operator is irreducible.

Tables 1 and 2 show timings for finding a right-hand factor of a product $L = L_1L_2$ of such operators of order $r/2$ having the same singularities, without trying to factor L completely. We compare Algorithm 3 to `DEtools[DFactor](...,'one step')`[5] in Maple. Factors are drawn either so that L has at least one exponential parts of multiplicity $\mu = 1$ at each singularity, or so that it has a single exponential part of multiplicity $\mu = r$ at each singularity. Unsurprisingly, `DEtools` performs well in the first scenario. As our algorithm then essentially reduces to van Hoeij's, it is expected that the timings are often comparable. The observed differences may be due to our use of numeric monodromy matrices with an ordinary base point and to time spent computing eigenrings in `DEtools`. In the case $\mu = r$, our implementation is faster. Moreover, for $r \geqslant 6$, `DEtools` outputs the warning 'factorization may be incomplete' and returns the operator L unfactored. We also note that both implementations (ours more than `DEtools`) show a large variability in their performance on operators of a given arithmetic size.

Tables 3 and 4 compare irreducibility testing on random operators of order r with ν finite singularities, with the same constraints on exponential parts as above. `DEtools` warns that 'factorization

[4]https://github.com/a-goyer/ore_algebra/tree/facto. The experiments reported here use commit `9e38de08`.

[5]With `_Env_eigenring_old` set to true, which usually performs significantly better.

may be incomplete' and gives up whenever $r \geq 5$, but is typically faster when it does conclude, thanks in part to dedicated algorithms for low orders [32]. For $r \geq 5$, our implementation can often prove irreducibility faster than it takes `DEtools` to give up. We observe that a small number of monodromy matrices typically suffices to conclude. However, the numeric precision needed can be very large even in irreducible cases. This is likely due to the fact that the monodromy matrices of our test operators tend to have large condition numbers ($\kappa \sim 10^{100}$ to $\kappa \sim 10^{1000}$).

A cooked-up example will amplify conditions that make the numeric approach win. We chose two operators P and Q with singularities at $0, 1, 2, \infty$, order 2, and integer exponents (thus exponential parts of multiplicity 2). The product QPP is reducible but indecomposable. We obtain an irreducible operator by considering $QPP+R$ for $R = (x(x-1)(x-2))^{-5}$. Our code finds another factorization of QPP in about 25 seconds and proves the irreducibility of $QPP + R$ in about the same time, while `DEtools` fails to find any factor of QPP in about 3 minutes and asserts the irreducibility of $QPP + R$ in a non-certified way in about the same time, in both cases admitting that 'factorization may be incomplete'.

μ=1		classic			new			behavior on median instance							
r	ν	min	med	max	min	med	max	class.	nb	mono.	nbits	tord	δs	δe	$\delta_{\mathbb{Z}}$e
4	2	0.38	0.44	0.67	1.3	3.7	5.6	**0.44**	2	86%	1600	64	9.3	68	1
4	3	0.75	0.84	1.7	3.7	9.3	59	**0.75**	2	94%	1436	48	0.08	48	–
4	4	2.1	2.5	2.7	2.6	6.4	14	**2.1**	3	90%	760	64	0.38	66	3
4	5	10	11	49	6.4	17	66	**11**	2	96%	1440	80	1.3	48	–
4	6	37	52	65	8.0	**33**	53	45	2	91%	1524	96	0.60	36	22
6	2	5.0	14	70	3.8	**8.5**	20	70	2	81%	1688	144	5.7	79	9
6	3	18	26	279	23	**39**	89	279	3	95%	2368	100	5.1	101	41
6	4	108	146	154	29	441	∞	**154**	2	100%	4764	100	1.3	105	18
6	5	218	328	1108	62	320	1180	**218**	2	99%	4356	100	1.4	40	6
6	6	1485	1906	2116	28	**302**	∞	1485	5	99%	2400	100	0.35	49	6
8	2	49	100	228	22	**48**	794	57	2	97%	3166	100	9.8	92	11
8	3	91	181	703	53	238	∞	**222**	2	97%	4064	200	4.8	41	24
8	4	373	401	496	158	1360	∞	**373**	2	100%	3420	100	1.3	114	–
8	5	1998	3055	∞	2630	∞	∞	∞	–	–	–	–	0.92	106	15
8	6	∞	∞	∞	∞	∞	∞	∞	–	–	–	–	0.08	109	24
10	2	206	476	2409	205	570	∞	**206**	2	99%	6396	100	1.4	65	11
10	3	442	949	1648	162	1010	∞	**442**	2	99%	4000	100	0.76	139	13
10	4	1937	3500	∞	∞	∞	∞	**3500**	–	–	–	–	1.5	99	15
10	5	∞	∞	∞	∞	∞	∞	∞	–	–	–	–	0.42	46	10
10	6	∞	∞	∞	∞	∞	∞	∞	–	–	–	–	0.38	106	16

Table 1: Comparison of `DEtools[DFactor]` with our new implementation on products of pairs of operators of order $r/2$ with ν finite singularities when multiplicity μ is 1. For each order r and number ν of finite singularities, we show the minimum, median, and maximum running times in seconds of `DEtools` in Maple 2022 (*classic*) and of our implementation running in Sage 9.5 (*new*) over the same set of 5 random operators. (All computations on an Intel i9-10885H processor, with concurrent jobs but system settings known to induce variations in performance disabled. Calculations stopped after 1 h.) We also collect statistics relative to the instance that realizes the median time with the "new" implementation: *class.* = corresponding "classic" time (s), *nb* = number of monodromy matrices computed, *mono.* = fraction of running time spent in monodromy computation, *nbits* = max. monodromy precision reached (bits), *tord* = max. series truncation order reached, δs = min. distance between two finite singular points, δe = max. exponent difference at the same singular point, $\delta_{\mathbb{Z}} e$ = max. integer exponent difference at the same singular point. Note that δe = $\delta_{\mathbb{Z}}$e when $\mu = r$, so that we do not display $\delta_{\mathbb{Z}}$e in Tables 2 and 4.

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μ=r		classic			new			behavior on median instance							
r	ν	min	med	max	min	med	max	class.	nb	mono.	nbits	tord	δ_s	$\delta_{\mathbb{Z}}$e	
4	2	0.22	0.32	2.3	0.92	3.1	3.3	**2.3**	2	76%	800	128	14	61	
4	3	96	343	690	3.7	**5.3**	30	690	2	86%	1472	48	2.9	110	
4	4	212	463	1907	7.7	**9.8**	15	270	3	91%	917	64	1.7	47	
4	5	602	711	1040	7.4	**16**	46	948	2	91%	865	80	2.6	50	
4	6	596	891	3022	21	**146**	976	3022	2	98%	2503	96	0.02	95	
6	2	*651*	*792*	*1047*	14	**103**	968	*792*	2	99%	3496	72	3.1	68	
6	3	*646*	*1670*	*2628*	22	**121**	1120	*646*	2	98%	3432	200	3.6	34	
6	4	*1118*	*2409*	∞	320	**491**	∞	*1760*	2	100%	3598	100	0.66	51	
6	5	*2557*	∞	∞	68	**212**	446	∞	2	99%	3170	100	0.73	122	
6	6	∞	∞	∞	731	**3360**	∞	∞	4	100%	6076	100	0.17	39	
8	2	*2392*	*2862*	∞	112	**311**	801	*2490*	2	99%	3692	200	4.4	66	
8	3	∞	∞	∞	254	**850**	∞	∞	2	100%	5198	100	3.1	107	
8	4	∞	∞	∞	484	∞	∞	∞	–	–	–	–	0.90	82	
8	5	∞	∞	∞	1620	∞	∞	∞	–	–	–	–	0.82	108	
8	6	∞	∞	∞	∞	∞	∞	∞	–	–	–	–	0.42	202	
10	2	∞	∞	∞	448	**3520**	∞	∞	2	100%	11968	200	8.9	107	
10	3	∞	∞	∞	2530	∞	∞	∞	–	–	–	–	3.8	226	
10	4	∞	∞	∞	∞	∞	∞	∞	–	–	–	–	1.3	78	
10	5	∞	∞	∞	∞	∞	∞	∞	–	–	–	–	0.11	58	
10	6	∞	∞	∞	∞	∞	∞	∞	–	–	–	–	0.80	47	

Table 2: Analogue of Table 1 when multiplicity μ is r. Italicized times indicate that `DEtools[DFactor]` gave up on factoring.

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μ=1		classic			new			behavior on median instance							
r	ν	min	med	max	min	med	max	class.	nb	mono.	nbits	tord	δ_s	δe	$\delta_{\mathbb{Z}}$e
2	2	0.12	0.13	0.14	0.45	0.54	0.72	**0.13**	2	86%	100	8	10	71	–
2	3	0.14	0.15	0.16	0.66	0.70	2.0	**0.15**	2	81%	100	12	0.19	35	–
2	4	0.14	0.15	0.16	0.47	1.3	1.5	**0.15**	4	83%	168	16	4.1	22	9
2	5	0.22	0.23	0.23	0.55	1.1	2.0	**0.23**	2	83%	190	20	0.03	26	–
2	6	0.30	0.32	0.33	0.69	1.0	4.0	**0.30**	2	80%	104	24	0.53	35	–
3	2	0.16	0.17	0.18	0.79	1.2	2.6	**0.16**	2	83%	460	36	1.8	88	–
3	3	0.31	0.32	0.32	1.1	2.4	9.4	**0.32**	3	83%	400	54	4.6	64	–
3	4	0.54	0.60	0.65	1.6	2.9	3.8	**0.54**	2	84%	762	36	3.8	83	8
3	5	1.6	1.7	1.8	2.7	20	712	**1.8**	3	98%	1600	45	0.24	17	–
3	6	2.8	5.2	5.3	2.1	7.8	609	**2.8**	4	95%	400	54	0.48	35	12
4	2	0.37	0.38	2.2	1.1	3.5	15	**0.38**	2	89%	1600	64	15	70	–
4	3	0.73	1.2	7.8	2.4	4.0	20	**1.2**	3	90%	665	48	4.2	62	11
4	4	2.0	2.4	2.5	1.4	15	∞	**2.5**	3	94%	1352	64	0.64	55	–
4	5	9.0	10	14	2.9	35	89	**11**	3	99%	1714	80	1.6	134	–
4	6	51	59	63	2.9	**11**	15	51	3	94%	780	96	0.14	72	31
5	2	*19*	*29*	*244*	1.3	**4.7**	6.9	*85*	2	93%	1200	50	1.4	41	–
5	3	*45*	*124*	*501*	7.3	**9.1**	34	*45*	3	96%	1200	75	3.8	36	–
5	4	*126*	*161*	*1007*	6.0	**89**	136	*161*	2	98%	4332	100	3.9	34	–
5	5	*449*	*1126*	∞	15	**103**	123	*1126*	3	100%	2396	100	1.6	111	–
5	6	*742*	*829*	*1560*	17	**346**	∞	*773*	2	99%	5516	100	0.44	44	–
6	2	*194*	*301*	*972*	2.5	**7.2**	75	*319*	2	90%	1372	72	5.9	62	–
6	3	*332*	*580*	*1804*	10	**770**	∞	*1177*	3	100%	5608	100	1.6	132	–
6	4	*710*	*923*	*3223*	17	**20**	3160	*3223*	3	97%	1052	100	3.0	156	22
6	5	*749*	*1874*	∞	33	**260**	∞	*1874*	2	100%	4146	100	1.4	69	29
6	6	∞	∞	∞	44	**197**	968	∞	2	98%	3184	100	1.0	34	–
7	2	*233*	*297*	*539*	24	**112**	∞	*297*	2	98%	3628	196	2.4	41	–
7	3	*512*	*1199*	∞	70	**549**	∞	*1199*	2	99%	7896	100	1.0	64	6
7	4	*922*	∞	∞	40	**1040**	∞	*1520*	3	100%	4104	100	0.60	60	–
7	5	*3085*	∞	∞	541	**1790**	∞	∞	2	100%	3952	100	0.55	96	12
7	6	∞	∞	∞	409	**1140**	∞	∞	2	99%	5912	100	2.0	133	–
8	2	*553*	*626*	*1496*	43	**353**	∞	*645*	2	99%	6980	200	2.5	54	–
8	3	*1315*	*2295*	*2897*	109	**708**	∞	*1525*	2	100%	5660	100	0.90	41	2
8	4	*2965*	∞	∞	38	∞	∞	∞	–	–	–	–	0.80	75	19
8	5	∞	∞	∞	2020	∞	∞	∞	–	–	–	–	0.14	37	30
8	6	∞	∞	∞	148	∞	∞	∞	–	–	–	–	0.30	96	21

Table 3: Comparison of `DEtools[DFactor]` with our new implementation on irreducible operators of order r with ν finite singularities when multiplicity μ is 1. Key as in Table 1. Italicized times indicate that `DEtools[DFactor]` issued 'factorization may be incomplete'.

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μ=r		classic			new			behavior on median instance						
r	ν	min	med	max	min	med	max	class.	nb	mono.	nbits	tord	δ_s	$\delta_{\mathbb{Z}e}$
2	2	0.13	0.18	0.23	0.46	1.2	1.4	**0.18**	2	88%	100	8	1.1	34
2	3	0.22	0.28	33	0.52	**1.1**	2.5	33	2	75%	100	24	3.6	60
2	4	0.24	0.31	2.1	0.89	4.1	7.8	**2.1**	2	94%	588	16	0.51	45
2	5	0.25	0.38	0.75	0.47	0.95	3.6	**0.38**	2	81%	100	20	0.74	40
2	6	0.28	0.59	1.3	0.67	1.5	6.9	**0.28**	2	86%	224	24	1.9	28
3	2	15	28	99	0.72	**2.4**	8.9	47	2	76%	1180	72	8.3	67
3	3	7.3	56	114	0.58	**1.1**	45	56	3	87%	230	27	3.1	54
3	4	41	69	234	7.4	**10.0**	20	234	2	94%	1106	36	3.3	102
3	5	119	176	424	2.1	**5.2**	30	176	3	92%	800	45	0.72	30
3	6	242	566	679	1.8	**5.5**	175	679	2	93%	728	54	2.0	99
4	2	71	107	178	5.1	**5.4**	435	178	2	91%	1600	64	17	91
4	3	90	162	174	2.1	**5.6**	66	167	3	89%	752	48	8.3	37
4	4	538	859	1183	200	1660	2160	**859**	2	99%	15380	64	0.76	104
4	5	616	810	1832	1.5	1100	∞	**780**	3	100%	2827	80	0.03	43
4	6	529	1292	∞	155	**448**	733	1105	2	100%	4841	96	0.69	36
5	2	*113*	*226*	*438*	3.5	**34**	147	*197*	2	97%	4800	100	8.8	39
5	3	*211*	*335*	*1778*	23	**32**	184	*335*	3	98%	1258	75	2.5	36
5	4	*487*	*732*	*1987*	51	**92**	∞	*487*	2	99%	2593	100	1.5	37
5	5	*1146*	*2956*	∞	140	**1590**	∞	∞	2	99%	4921	100	0.54	104
5	6	*2216*	*3542*	∞	17	**611**	1950	∞	2	100%	4752	100	0.02	71
6	2	*129*	*414*	*716*	6.3	**14**	33	*129*	2	96%	2400	72	13	24
6	3	*957*	*1707*	*3202*	51	**1680**	∞	*3202*	3	100%	7714	100	1.9	74
6	4	*1194*	*2567*	∞	∞	∞	∞	***2567***	–	–	–	–	0.12	54
6	5	*2985*	∞	∞	344	2990	∞	***2985***	3	100%	6556	100	0.53	36
6	6	∞	∞	∞	1150	**2350**	∞	∞	2	100%	9578	100	1.0	49
7	2	*556*	*1198*	*1533*	36	756	3560	***556***	2	100%	5020	98	3.2	35
7	3	*1367*	∞	∞	166	**859**	∞	*1367*	3	100%	5006	100	6.4	38
7	4	∞	∞	∞	1860	**2850**	∞	∞	2	100%	9088	100	0.81	160
7	5	∞	∞	∞	200	**1050**	∞	∞	2	100%	4636	100	0.94	132
7	6	∞	∞	∞	824	∞	∞	∞	–	–	–	–	0.01	55
8	2	*679*	∞	∞	158	**1970**	∞	∞	2	99%	9004	100	18	103
8	3	∞	∞	∞	926	**2140**	∞	∞	2	100%	9592	100	10	111
8	4	∞	∞	∞	∞	∞	∞	∞	–	–	–	–	1.9	146
8	5	∞	∞	∞	∞	∞	∞	∞	–	–	–	–	1.3	241
8	6	∞	∞	∞	∞	∞	∞	∞	–	–	–	–	0.19	122

Table 4: Analogue of Table 3 when multiplicity μ is r.

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