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A FAST AND NEARLY DIVISION-FREE ALGORITHM FOR THE CHARACTERISTIC POLYNOMIAL

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ABSTRACT. We give a simple $O(n^{3.5})$ algorithm for computing the characteristic polynomial, determinant and adjugate of an $n \times n$ matrix, using only ring operations together with exact divisions by small integers. The method is a baby-step giant-step version of the Faddeev-Leverrier algorithm.

1. Introduction

Let R be a commutative ring. Denote by $\omega > 2$ an exponent of matrix multiplication, meaning that we can multiply two $n \times n$ matrices using $O(n^\omega)$ ring operations (additions, subtractions and multiplications). Assume additionally that R has a unit and that the characteristic of R is 0 or coprime to $1, 2, \ldots, n$. We shall describe a simple algorithm that achieves the following:

Theorem 1. *The characteristic polynomial, determinant and adjugate of a matrix $A \in R^{n \times n}$ can be computed using $O(n^{\omega+0.5} + n^3)$ ring operations in R and n exact divisions of elements in R by integers $1 \le k \le n$.*

The complexity reduces to $O(n^{3.31})$ with Strassen multiplication ($\omega = \log_2(7)$), and $O(n^3)$ with the asymptotically fastest currently known multiplication algorithm ($\omega = 2.3728639$) due to Le Gall [9]. Since Strassen's algorithm tends to give modest savings and Le Gall's algorithm is completely impractical, the $O(n^{3.5})$ complexity with classical $\omega = 3$ multiplication is perhaps the most relevant metric.

The method is a baby-step giant-step improvement of the Faddeev-Leverrier algorithm, which in its original form (Algorithm 1) achieves the same result with complexity $O(n^{\omega+1})$. Although our improvement (Algorithm 2) is elementary, it has apparently never been published. Csanky [6] describes a parallel version of the Faddeev-Leverrier algorithm; Berkowitz [2] states that this can be turned into an $O(n^{\omega+0.5} \log n)$ method using baby-step giant-step techniques, citing private communication with S. Winograd, but does not describe such an algorithm in detail. Since all descriptions of the Faddeev-Leverrier algorithm that we have found in the literature present it as an $O(n^4)$ or $O(n^{\omega+1})$ algorithm, it seems appropriate to document an improved version and study its performance.

If R is a field, then the determinant, adjugate and characteristic polynomial can be computed in $O(n^\omega)$ operations allowing divisions [8, 21, 1, 19]. The same is also true if R is an integral domain (for example, by working in its fraction field). The key point of Theorem 1 is that the algorithm is *nearly division-free*, in the sense that we do not divide by general elements of R (all divisors are integers, and the divisions are *exact* in the sense that the quotients remain in R). It is also *branch-free*: we do not need to determine whether elements in R are zero. It is an open problem whether an $O(n^\omega)$ algorithm is possible with these constraints.

The obvious division-free algorithm is cofactor expansion, which uses $O(n!)$ operations. It is mainly interesting for $n \leq 4$ and for sparse symbolic matrices. The *Berkowitz algorithm* [2] achieves complexity $O(n^{\omega+1})$ without any divisions, and at least with classical multiplication is faster than the original Faddeev-Leverrier algorithm by a constant factor since it operates on triangular matrices rather than full matrices. Our improved Faddeev-Leverrier algorithm overcomes this disadvantage asymptotically. It is an open problem (already posed in [2]) whether the Berkowitz algorithm admits a similar baby-step giant-step speedup.

Neither Theorem 1 nor the complexity claimed by Berkowitz is the best result available for linear algebra over rings. Kaltofen and Gillard have shown [17, 18, 26] that the determinant and adjoint of a matrix over any commutative ring can be computed without divisions in $n^{\eta+o(1)}$ operations where $\eta = \omega+1/((\omega-1)^2+1)$, and similarly the bound $n^{\chi+o(1)}$ with $\chi = \omega+2/(\omega^2-\omega+1)$ holds for the characteristic polynomial. This gives $\eta = \omega + 0.2$ and $\chi \approx \omega + 0.29$ with classical multiplication ($\omega = 3$) and $\eta \approx \omega + 0.35$, $\chi \approx \omega + 0.47$ with Le Gall's algorithm.[1] The Kaltofen-Gillard algorithm is quite complex, however, requiring (among other things) FFT-based multiplication of power series matrices. Theorem 1 has a slightly worse exponent and requires division by integers, but the algorithm can be implemented in a few lines of code using only matrix multiplication as a building block.

2. The Faddeev-Leverrier algorithm

We recall the Faddeev-Leverrier algorithm (see [25, 12, 6, 13]; Alg. 2.2.7 in [5]) for computing the characteristic polynomial $p_A(x) = c_n x^n + \cdots + c_1 x + c_0$ of a square matrix A. The algorithm is based on the recursion $c_{n-k} = -\frac{1}{k}\sum_{j=1}^{k} c_{n-k+j}\,\mathrm{Tr}(A^j)$: we compute a sequence of matrices (stored in the variable B) through repeated multiplication by A, and in each step extract a trace. The determinant and the adjugate matrix appear as byproducts of this process: $(-1)^n \det(A)$ is the last coefficient c_0, and $(-1)^{n+1}\,\mathrm{adj}(A)$ is the penultimate entry in the matrix sequence.

Algorithm 1 Faddeev-Leverrier algorithm

Input: $A \in R^{n\times n}$ where $n \geq 1$ and R is a commutative ring, R having a unit element and characteristic 0 or characteristic coprime to $1, 2, \ldots, n$
Output: $(p_A(x),\ \det(A),\ \mathrm{adj}(A))$

$c_n = 1, \quad B \leftarrow I, \quad k \leftarrow 1$
while $k \leq n-1$ **do**
    $B \leftarrow AB$
    $c_{n-k} \leftarrow -\frac{1}{k}\,\mathrm{Tr}(B)$
    $B \leftarrow B + c_{n-k}\,I$
    $k \leftarrow k+1$
end while
$c_0 \leftarrow -\frac{1}{n}\,\mathrm{Tr}(AB)$
return $(c_0 + c_1 x + \ldots + c_n x^n,\ (-1)^n c_0,\ (-1)^{n+1} B)$

The code can be tightened assuming $n \geq 2$, in which case the line before the start of the loop can be changed to $\{c_n = 1,\ c_{n-1} = -\,\mathrm{Tr}(A),\ B \leftarrow A + c_{n-1}I,\ k \leftarrow 2\}$.

[1] Slightly better η and χ can be given by using fast rectangular matrix multiplication.

We can change the loop condition to $k \leq n$ and remove the line after the loop if we omit returning $\text{adj}(A)$.

It is easy to see that Algorithm 1 performs $O(n)$ matrix multiplications and $O(n^2)$ additional arithmetic operations. The condition on the characteristic of R ensures that we can divide exactly by each k, i.e. $(xk)/k = x$ holds for $x \in R, k \leq n$.

3. The improved Faddeev-Leverrier algorithm

Algorithm 1 computes a sequence of n matrices but only extracts a small amount of unique information (the trace) from each matrix. In such a scenario, we can often save time using a baby step giant-step approach in which we only compute $O(\sqrt{n})$ products explicitly (see [20, 3, 2, 14] for a few examples of this technique). The key observation in this instance is that, given matrices A and B, we can compute $\text{Tr}(AB)$ using $O(n^2)$ operations without forming the complete matrix product AB, by simply evaluating the dot products for the main diagonal of AB. We denote this *product trace* operation by $\text{Tr}(A, B)$.

We now choose a step size $m \approx \sqrt{n}$, expand the loop in Algorithm 1 to group m iterations together, and precompute the matrix powers and traces that appear repeatedly. This results in Algorithm 2.

Algorithm 2 Baby-step giant-step Faddeev-Leverrier algorithm

Input: $A \in R^{n \times n}$ where $n \geq 1$ and R is a commutative ring, R having a unit element and characteristic 0 or characteristic coprime to $1, 2, \ldots, n$

Output: $(p_A(x),\ \det(A),\ \text{adj}(A))$

$m \leftarrow \lfloor \sqrt{n} \rfloor$
Precompute the matrices $A^1, A^2, A^3, \ldots, A^m$
Precompute the traces $t_k = \text{Tr}(A^k)$ for $k = 1, \ldots, m$
$c_n = 1, \quad B \leftarrow I, \quad k \leftarrow 1$
while $k \leq n - 1$ **do**
    $m \leftarrow \min(m, n - k)$
    $c_{n-k} \leftarrow -\frac{1}{k} \text{Tr}(A, B)$
    for $j \leftarrow 1, 2, \ldots, m - 1$ **do**
        $c_{n-k-j} \leftarrow \text{Tr}(A^{j+1}, B)$ ▷ Using precomputed power of A
        for $i \leftarrow 0, 1, \ldots, j - 1$ **do**
            $c_{n-k-j} \leftarrow c_{n-k-j} + t_{j-i} c_{n-k-i}$
        end for
        $c_{n-k-j} \leftarrow c_{n-k-j}/(-k - j)$
    end for
    $B \leftarrow A^m B$ ▷ Using precomputed power of A
    for $j \leftarrow 0, 1, \ldots, m - 1$ **do**
        $B \leftarrow B + c_{n-k-j} A^{m-j-1}$ ▷ Using precomputed power, or $A^0 = I$
    end for
    $k \leftarrow k + m$
end while
$c_0 \leftarrow -\frac{1}{n} \text{Tr}(A, B)$
return $(c_0 + c_1 x + \ldots + c_n x^n,\ (-1)^n c_0,\ (-1)^{n+1} B)$

The complexity bound in Theorem 1 is clear from inspection since we perform $O(m + n/m) = O(\sqrt{n})$ matrix multiplications of size $n \times n$, and $O(n^3)$ arithmetic

operations in the remaining steps. The remaining $O(n^3)$ operations can presumably be grouped into matrix multiplications with further rearrangements; this might lead to the complexity bound suggested by Berkowitz, but we have not attempted to pursue such an analysis since any asymptotic savings would be irrelevant for practical computations.

As an observation for implementations, the matrix-matrix multiplications and product traces are done with invariant operands that get recycled $O(\sqrt{n})$ times. This can be exploited for preconditioning purposes, for instance by packing the data more efficiently for arithmetic operations. We also note that the optimal m may depend on the application, and a smaller value will reduce memory consumption.

4. Applicability and performance evaluation

When, if ever, does it make sense to use Algorithm 2? We can immediately discard some applications:

- For computing over $\mathbb{R}$ and $\mathbb{C}$ in ordinary floating-point arithmetic, the Faddeev-Leverrier algorithm is slower and far less numerically stable than textbook techniques such as reduction to Hessenberg form and Gaussian elimination with $O(n^3)$ or better complexity [22, 27].
- For finite fields, classical $O(n^3)$ methods using divisions have no drawbacks, and linear algebra with $O(n^{2.81})$ Strassen complexity is well established [7]. Over rings with small characteristic, the applicability of Algorithm 2 is in any case limited due to the integer divisions.

Generally speaking, division-free or nearly division-free algorithms are interesting for rings and fields R where dividing recklessly can lead to coefficient explosion (for example, $\mathbb{Q}$) or in which testing for zero is problematic (for example, exact models of $\mathbb{R}$). The optimal approach in such situations is usually to avoid computing directly in R, for example using modular arithmetic and interpolation techniques, but such indirect methods are more difficult to implement and must typically be designed on a case by case basis. By contrast, Algorithm 2 is easy to use anywhere. We will now look at the results of some implementation experiments.

4.1. Integers.

For exact linear algebra over $\mathbb{Z}$ and $\mathbb{Q}$, the best methods are generally fraction-free versions of classical algorithms (such as the Bareiss version of Gaussian elimination) for small n, and multimodular or p-adic methods for large n (see for example [8, 21]). We do not expect Algorithm 2 to beat those algorithms, but it is instructive to examine its performance. Table 1 shows timings for computing a determinant, inverse or characteristic polynomial of an $n \times n$ matrix over $\mathbb{Z}$ with random entries in $-10, \ldots, 10$, using the following algorithms:

- FFLU: fraction-free LU factorization using the Bareiss algorithm.
- FFLU2: as above, but using the resulting decomposition to compute A^{-1} (equivalently determining $\operatorname{adj}(A)$) by solving $AA^{-1} = I$.
- ModDet: a multimodular algorithm for the determinant.
- ModInv: a multimodular algorithm for the inverse matrix.
- ModCP: a multimodular algorithm for the characteristic polynomial.
- Berk: the Berkowitz algorithm for the characteristic polynomial.
- Alg1: Faddeev-Leverrier, Algorithm 1.
- Alg2: baby-step giant-step Faddeev-Leverrier, Algorithm 2.

TABLE 1. Time in seconds to compute characteristic polynomial (C), determinant (D), adjugate/inverse (A) of an $n \times n$ matrix over $\mathbb{Z}$ with random elements in $-10, \ldots, 10$, using various algorithms.

n	FFLU D	ModDet D	FFLU2 DA	ModInv A	ModCP CD	Berk CD	Alg1 CDA	Alg2 CDA
10	0.0000060	0.000021	0.000015	0.00012	0.000016	0.000035	0.000015	0.000030
20	0.000036	0.000078	0.00043	0.00096	0.00011	0.0010	0.00086	0.00061
50	0.0023	0.0012	0.011	0.016	0.0039	0.048	0.052	0.017
100	0.039	0.0068	0.14	0.18	0.055	0.84	1.1	0.22
200	0.64	0.044	2.3	1.8	0.89	16	27	4.1
300	3.4	0.15	13	9.0	4.6	94	174	20
400	12	0.38	45	22	15	321	696	66
500	32	0.77	127	52	37	900	2057	150

We implemented Alg1 and Alg2 on top of Flint [10], while all the other tested algorithms are builtin Flint methods.

4.1.1. *Observations.* Alg2 clearly outperforms both Alg1 and Berk for large n, making it the best algorithm for computing the characteristic using direct arithmetic in $\mathbb{Z}$ (the modular algorithm is, as expected, superior). Alg2 is reasonably competitive for computing the inverse or adjugate matrix, coming within a factor 2-3$\times$ of FFLU2 and ModInv in this example. For determinants, the gap to the FFLU algorithm is larger, and the modular determinant algorithm is unmatched.

4.2. **Number fields.** Exact linear algebra over algebraic number fields $\mathbb{Q}(a)$ is an interesting use case for division-free algorithms since coefficient explosion is a significant problem for classical $O(n^3)$ algorithms. As in the case of $\mathbb{Z}$ and $\mathbb{Q}$, modular algorithms are asymptotically more efficient than working over $\mathbb{Q}(a)$ directly, but harder to implement. Here we compare the following algorithms:

- Sage: the `charpoly` method in SageMath [24], which implements a special-purpose algorithm for cyclotomic fields based on modular computations and reconstruction using the Chinese remainder theorem.
- Hess: Hessenberg reduction for the characteristic polynomial
- Dani: Danilevsky's algorithm for the characteristic polynomial.
- LU: LU factorization to compute the determinant.
- FFLU: fraction-free LU factorization using the Bareiss algorithm.
- LU2 and FFLU2: as above, but using the resulting decomposition to compute A^{-1} (equivalently determining $\operatorname{adj}(A)$) by solving $AA^{-1} = I$.
- Berk (Berkowitz), Alg1 and Alg2 as in the previous section.

With the exception of the Sage function, we implemented all the algorithms using Antic [11] for number field arithmetic and Flint for other operations. We perform fast matrix multiplication by packing number field elements into integers and multiplying matrices over $\mathbb{Z}$ via Flint. Our implementations of LU, LU2, Alg1 and Alg2 benefit from matrix multiplication while Hess, Dani, FFLU, FFLU2 and Berk do not. The benchmark is therefore not representative of the performance that ideally should be achievable with these algorithms, although it is fair in the

TABLE 2. Time in seconds to compute characteristic polynomial (C), determinant (D), adjugate/inverse (A) of a matrix over a cyclotomic number field.

n	Sage CD	Hess CD	Dani CD	LU D	FFLU D	LU2 DA	FFLU2 DA	Berk CD	Alg1 CDA	Alg2 CDA
Input: $n \times n$ matrix over $\mathbb{Q}(\zeta_{20})$, entries $\sum_k (p/q)\zeta_{20}^k$, random $\lvert p\rvert \leq 10$, $1 \leq q \leq 10$.										
10	0.038	0.31	0.16	0.024	0.0059	0.21	0.11	0.010	0.0073	0.010
20	0.12	19	6.7	0.22	0.067	2.6	1.4	0.28	0.15	0.16
30	0.39	200	67	0.93	0.31	12	6.8	2.0	1.1	0.8
40	1.1		353	2.8	0.9	37	22	7.5	3.7	2.6
50	1.9			7.0	2.3	88	56	22	8.7	5.7
60	3.4			15	4.7	182	119	54	19	12
70	5.1			29	8.6	337	230	114	39	22
80	7.5			53	15	581	409	208	67	34
90	11			89	24			397	144	54
100	15			144	41			608	670	130
120				322	83			1439	3013	420
Input: $n \times n$ DFT matrix over $\mathbb{Q}(\zeta_n)$, entries $A_{i,j} = \zeta_n^{(i-1)(j-1)}$.										
10	0.010	0.0018	0.0016	0.00017	0.00022	0.00076	0.0014	0.00061	0.00075	0.00059
20	0.039	0.0019	0.0024	0.0017	0.0046	0.0071	0.038	0.020	0.020	0.0070
50	1.3	0.17	0.13	0.065	0.80	0.28	6.0	8.2	2.0	0.49
100	22	5.4	22	0.89	43	5.3	335	803	223	29
150	78	22	7.9	4.4	214	19	1423	7259	933	138
200	333	1928	140	31	1655	192				1687

sense that the implementation effort for Alg1 and Alg2 was minimal while the other algorithms would require much more code to speed up using block strategies.

Table 2 compares timings for two kinds of input: random matrices over a fixed cyclotomic field, and discrete Fourier transform (DFT) matrices which have special structure. Choosing cyclotomic fields allows us to compare with the dedicated algorithm for characteristic polynomials in Sage; the corresponding method for generic number fields in Sage is far slower. All the other algorithms make no assumptions about the field.

4.2.1. *Observations.* There are no clear winners since there is a complex interplay between operation count, multiplication algorithms, matrix structure and coefficient growth. Modular algorithms are the best solution in general for large n, but implementations for number fields are complex and less readily available in current software than for $\mathbb{Z}$ and $\mathbb{Q}$.

Among the non-modular algorithms, the $O(n^3)$ division-heavy Hessenberg and Danilevsky algorithms are nearly useless due to coefficient explosion for generic input, but both perform well on the DFT matrix. The LU and FFLU algorithms have more even performance but alternate with each other for the advantage depending on the matrix. Alg2 has excellent average performance for the determinant, characteristic polynomial as well as the adjugate matrix considering the large variability between the algorithms for different input. It is highly competitive for computing the inverse or adjugate of the random matrix.

TABLE 3. Time in seconds to compute characteristic polynomial (C), determinant (D), adjugate/inverse (A) of a random $n \times n$ matrix in real ball arithmetic. The respective algorithms were run with $333 + p$ bits of precision, with p chosen to give roughly 100-digit output accuracy.

n	Hess CD	Hess2 CD	Dani CD	Eig CD	LU D	LU2 D	Berk CD	Alg1 CDA	Alg2 CDA
10	0.00021	0.00038	0.00022	0.017	0.000068	0.00023	0.00080	0.0010	0.00078
20	0.0021	0.0032	0.0020	0.18	0.00052	0.0015	0.0039	0.017	0.0092
50	0.045	0.057	0.048	4.6	0.0078	0.019	0.22	0.61	0.21
100	0.64	0.69	0.61	56	0.062	0.15	6.3	9.7	2.4
150	3.5	3.5	3.0	245	0.23	0.44	52	52	11
200	12	11	10		0.59	1.0	224	176	34
250	31	29	25		1.4	1.9	687	460	73
300	66	59	53		2.5	3.2	1804	1075	160
350	135	115	110		4.4	5.0	4033	2107	306
p	$10n$	$6n$	$10n$	0	n	0	$6n$	$6n$	$6n$

4.3. **Ball arithmetic.** Division-free algorithms are useful when computing rigorously over $\mathbb{R}$ and $\mathbb{C}$ in interval arithmetic or ball arithmetic. The reason is that we cannot test whether elements are zero, so algorithms like Gaussian elimination and Hessenberg reduction fail when they need to branch upon zero pivot elements or zero vectors. Although zeros will not occur for random input, they are likely to occur for structured matrices arising in applications. *A posteriori* verification of approximate numerical solutions or perturbation analysis is in principle the best workaround [23], but it is sometimes useful to fall back to more direct division-free methods, especially when working in very high precision.

Table 3 shows timings for computing a determinant or characteristic polynomial with 100-digit accuracy using the following algorithms implemented in ball arithmetic. The input is taken to be an $n \times n$ real matrix with uniformly random entries in $[0, 1]$. For this experiment, we only focus on the determinant and characteristic polynomial (the conclusions regarding matrix inversion would be similar to those regarding the determinant).

- Hess: Hessenberg reduction using Gaussian elimination.
- Hess2: Hessenberg reduction using Householder reflections.
- LU: LU factorization using Gaussian elimination.
- LU2: approximate computation of the determinant using LU factorization followed by *a posteriori* verification.
- Eig: approximate computation of the eigenvalues using the QR algorithm followed by *a posteriori* verification and reconstruction of the characteristic polynomial from its roots.
- Berk (Berkowitz), Alg1 and Alg2 as in the previous section.

All algorithms were implemented in Arb[15] which uses the accelerated dot product and matrix multiplication algorithms described in [16]. The LU, LU2, Alg1 and Alg2 implementations benefit from fast matrix multiplication while Hess, Hess2, Eig and Berk do not.

The methods LU2 and Eig are numerically stable: the output balls are precise to nearly full precision for well-conditioned input. All other algorithms are unstable in ball arithmetic and lose $O(n)$ digits of accuracy. At least on this example, the rate of loss is almost the same for Hess2, Berk, Alg1 and Alg2, while LU is more stable and Hess and Dani are less stable. To make the comparison meaningful, we set the working precision (shown in the table) to an experimentally determined value so that all algorithms enclose the determinant with around 100 digits of accuracy.

4.3.1. *Observations.* For computing the characteristic polynomial in high-precision ball arithmetic, it seems prudent to try Hessenberg reduction and fall back to a division-free algorithm when it fails due to encountering a zero vector. The Berkowitz algorithm is the best fallback for small n, while Alg2 wins for large n ($n \approx 50$, although the cutoff will vary). On this particular benchmark, Alg2 runs only about $4\times$ slower than Hessenberg reduction, making it an interesting *one-size-fits-all* algorithm. The verification method (Eig) gives the best results if the precision is constrained, but is far more expensive than the other methods.

For computing the determinant alone, all the division-free methods are clearly inferior to methods based on LU factorization in this setting. The only advantage of the division-free algorithms is that they are foolproof while LU factorization requires some attention to implement correctly.

Better methods for computing the characteristic polynomial in ball arithmetic or interval arithmetic are surely possible. For the analogous problem of computing the characteristic polynomial over $\mathbb{Q}_p$, see [4].

4.4. **Polynomial quotient rings.** At first glance Algorithm 2 seems to hold potential for working over multivariate polynomial quotient rings. Such rings need not be integral domains and division can be very expensive (requiring Gröbner basis computations). Unfortunately, in most examples we have tried, Algorithm 2 performs worse than both the Berkowitz algorithm and Algorithm 1, presumably because repeated multiplication by the initial matrix A is much cheaper than multiplication by a power of A which generally will have much larger entries. There may be special classes of matrices for which the method performs well, however.

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