

Computing Characteristic Polynomials of p -Curvatures in Average Polynomial Time

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Differential equations in characteristic p

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- *the dimension of the space of solutions that are algebraic over $\mathbb{F}_p(z)$*
- *the dimension of the kernel of the p -curvature of this differential equation.*

p -curvature in characteristic 0

Conjecture (Grothendieck-Katz)

A linear differential equation in characteristic 0 admits an algebraic basis of solutions over $\mathbb{Q}(z)$ iff its reduction modulo p has an algebraic basis of solutions over $\mathbb{F}_p(z)$ for all primes p except a finite number.

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Theorem (Chudnovsky)

If $f \in \mathbb{Z}[[z]]$ (with non zero convergence radius) is a solution of a linear differential equation, then the minimal differential equation for f is globally nilpotent.

Useful for guessing procedures.

Other applications

- Algorithms for factoring differential operators using p -curvatures
[CLUZEAU, ISSAC 2003]

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- Algorithms for computing the Lie algebra of differential operators
[BARKATOU, CLUZEAU, DI VIZIO, WEIL, ISSAC 2016]

Algebra of Differential operators

Definition

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$$\partial f = f\partial + f'$$

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The p -curvature of an operator $L \in \mathbb{F}_p(z)\langle\partial\rangle$ is the $\mathbb{F}_p(z)$ -linear endomorphism of $\mathbb{F}_p(z)\langle\partial\rangle/\mathbb{F}_p\langle\partial\rangle L$ induced by the left multiplication by ∂^p .

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Cost: $\tilde{O}(p^2)$ binary operations.

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Size: $\chi(A_p(L))$ is of bit size $O(\log(p))$.

Previous works around the computation of p -curvatures

- First subquadratic time algorithm for computing the p -curvature [BOSTAN, SCHOIST, ISSAC 2009].

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My Contribution: Theoretical part

Theorem (P., 2021)

It is possible to compute, for a given linear differential equation with coefficients in $\mathbb{Z}[\tilde{z}]$, the characteristic polynomials of its p -curvatures for all primes $p < N$ in $\tilde{O}(N)$ binary operations.

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Theorem (P., 2021)

It is possible to compute, for a given linear differential equation with coefficients in $\mathbb{Z}[z]$ of order m , with polynomial coefficients of degree at most d and integer coefficients of bit size at most n , all the characteristic polynomials of its p -curvatures for all primes $p < N$ in

$$\tilde{O}(Nd((n + d)(m + d)^\omega + (m + d)^\Omega))$$

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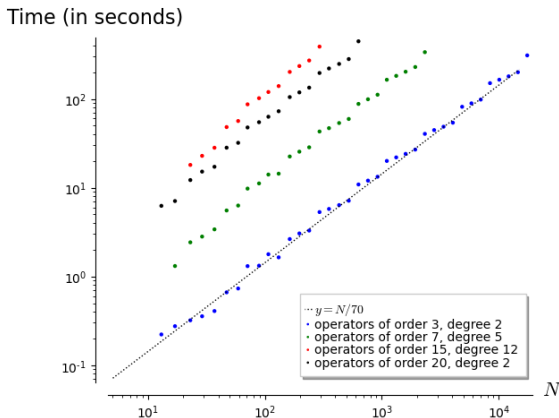
binary operations.

$\omega < 2,373$ is an exponent of matrix multiplication in any ring.

$\Omega < 2,698$ is an exponent for the computation of the characteristic polynomial in any ring.

My Contribution: Practical part

Implementation of the algorithm in Sagemath



Computation of p -curvatures

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Step 2: Use the factorial computation method of [COSTA, GERBICZ, HARVEY, Math. Comp. 2014]

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$$\Phi_p : \mathbb{F}_p[z]\langle\partial^{\pm 1}\rangle \xrightarrow{\sim} \mathbb{F}_p[\theta]\langle\partial^{\pm 1}\rangle$$

Two crucial maps: $\Xi_{z,\partial}$ and $\Xi_{\theta,\partial}$

Definition

Let $L_\theta \in \mathbb{F}_p(\theta)\langle\partial\rangle$. Its p -curvature $B_p(L_\theta)(\theta)$ is the $\mathbb{F}_p(\theta)$ -linear endomorphism of $\mathbb{F}_p(\theta)\langle\partial\rangle/\mathbb{F}_p(\theta)\langle\partial\rangle L_\theta$ induced by the left multiplication by ∂^p .

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If $B = B(L_\theta)(\theta)$ is its companion matrix then:

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Let $L_z \in \mathbb{F}_p(z)\langle\partial\rangle$ (resp. $L_\theta \in \mathbb{F}_p(\theta)\langle\partial\rangle$) with leading coefficient l_z (resp. l_θ).

$$\Xi_{z,\partial}(L_z) := l_z(z)^p \chi(A_p(L_z))(\partial^p)$$

$$\Xi_{\theta,\partial}(L_\theta) := \left(\prod_{i=0}^{p-1} l_\theta(\theta + i) \right) \chi(B_p(L_\theta))(\partial^p)$$

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- Multiplicativity: $\Xi_{\cdot,\partial} : \mathbb{F}_p(\cdot)\langle\partial^{\pm 1}\rangle \rightarrow \mathbb{F}_p(\cdot)\langle\partial^{\pm p}\rangle$.

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Theorem (Bostan, Caruso, Schost, ISSAC 2014)

The applications $\Xi_{\cdot,\partial}$ commute with the isomorphism Φ_p :

$$\begin{array}{ccc}
 k[x]\langle\partial^{\pm 1}\rangle & \xrightarrow[\sim]{\Phi_p} & k[\theta]\langle\partial^{\pm 1}\rangle \\
 \downarrow \Xi_{x,\partial} & & \downarrow \Xi_{\theta,\partial} \\
 k[x^p][\partial^{\pm p}] & \xrightarrow[\sim]{\Phi_p} & k[\theta^p - \theta][\partial^{\pm p}]
 \end{array}$$

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$$(z+1)^2\partial^3 - z\partial + z^3 + 3$$

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$$(z+1)^2\partial^3 - z\partial + z^3 + 3 \quad \mapsto \quad \partial^3 + 2\theta\partial^2 + (\theta^2 - \theta)\partial - (\theta + 3) + (\theta^3 - 3\theta^2 + 2\theta)\partial^{-3}$$

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$$(z^5+1)^2\partial^{15} + (4z^5+2)\partial^5 + z^{15} + 2z^5$$

$$\begin{aligned} & \partial^{15} + 2(\theta^5 - \theta)\partial^{10} \\ & + ((\theta^5 - \theta)^2 + 2)\partial^5 + 4(\theta^5 - \theta) \\ & + 2(\theta^5 - \theta)\partial^{-5} + (\theta^5 - \theta)^3\partial^{-15} \end{aligned}$$

Extension to integral coefficients

$$\Phi : \mathbb{Z}[z]\langle \partial^{\pm 1} \rangle \xrightarrow{\sim} \mathbb{Z}[\theta]\langle \partial^{\pm 1} \rangle$$

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$B(\theta)$ is the companion matrix of $\Phi(L)$.

$$B(\theta)B(\theta + 1) \cdots B(\theta + p - 1) \equiv \text{mod } p \text{ for all } p < N.$$

A first simplification

If $L \in \mathbb{Z}[z]\langle\partial\rangle$ has coefficients of degree at most d , then $\Xi_{\theta,\partial}(L)$ has coefficients of degree at most d in $\theta^p - \theta$.

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Lemma

It is possible to determine entirely $P \in \mathbb{F}_p[\theta^P - \theta]$ of degree dp in θ from its first d coefficients.

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Conclusion: All computations can be done modulo θ^{d+1} .

Computation of $(p-1)! \bmod p^s$ [COSTA, GERBICZ, HARVEY, 2014]

$$N = 7.$$

$$(3-1)!$$

Computation of $(p-1)! \bmod p^s$ [COSTA, GERBICZ, HARVEY, 2014]

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$$((5-1)! \bmod 5^s 7^s) \times (5 \times 6) \bmod 7^s$$

Computation of $B(\theta) \cdots B(\theta + p - 1) \pmod p$

$N = 7$.

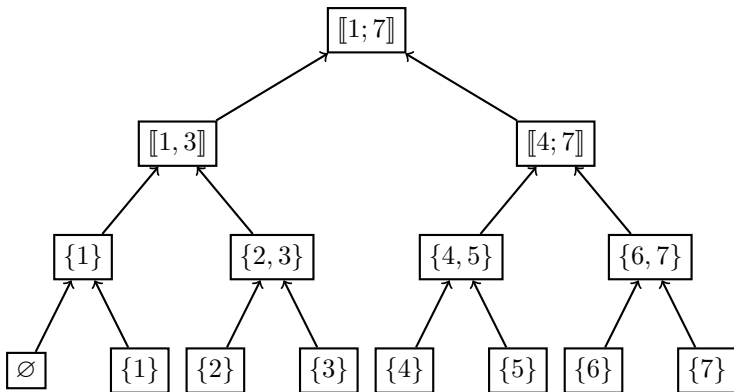
$$\begin{array}{ccc} B(\theta)B(\theta+1)B(\theta+2) & B(\theta) \cdots B(\theta+4) & B(\theta) \cdots B(\theta+6) \\ \pmod{3 \times 5 \times 7} & \pmod{5 \times 7} & \pmod{7} \end{array}$$

$$(B(\theta)B(\theta+1)B(\theta+2) \pmod{3 \times 5 \times 7}) \times (B(\theta+3)B(\theta+4) \pmod{5 \times 7})$$

$$(B(\theta) \cdots B(\theta+4) \pmod{5 \times 7}) \times (B(\theta+5)B(\theta+6) \pmod{7})$$

Remainder tree.

Computation of $(p-1)! \bmod p^s$ [COSTA, GERBICZ, HARVEY, 2014]



Future works

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THANK YOU FOR YOUR ATTENTION