Computing Minimal Polynomials

Max Neunhöffer

Lehrstuhl D für Mathematik
RWTH Aachen

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All of this is joint work with Cheryl Praeger

and is based on earlier ideas of

Peter Neumann and Cheryl Praeger.

The Problem

An example

Baby Monster group $B = \langle a, b \rangle$ with $a, b \in \mathbb{F}_2^{4370 \times 4370}$
Consider $M := a + b + ab \in \mathbb{F}_2^{4370 \times 4370}$

Computing

- the characteristic polynomial χ_M of M takes $8.5s$
- the minimal polynomial μ_M of M takes $9600s$

(times in GAP, other systems behave similarly).

Questions

What is going on here?

What can we do about this?

Is this a typical example?

Order polynomials

Definition (Order polynomial)

$\mathbb{F}$ field, $\mathcal{A}$ f.d. $\mathbb{F}$-algebra, $V \in$ mod-$\mathcal{A}$, $v \in V$, $M \in \mathcal{A}$.
Then the **order polynomial** $q := \mathrm{ord}_M(v) \in \mathbb{F}[x]$ is the monic polynomial of least degree such that $v \cdot q(M) = 0$.

Definition (Relative order polynomial)

If additionally $W < V$ is M-invariant, then we call $\mathrm{ord}_M(v + W)$ the **relative order polynomial** of $v + W \in V/W$.

Lemma (Generator of annihilator)

The order polynomial $\mathrm{ord}_M(v)$ divides every polynomial $q \in \mathbb{F}[x]$ with $v \cdot q(M) = 0$.

The standard approach

What is going on here?

The characteristic polynomial

Let $v_1, \ldots, v_i \in V$, and $V_i := \langle v_1, \ldots, v_i \rangle_M$ the $\mathbb{F}[M]$-span. Find smallest $d_1 \in \mathbb{N}$ such that $(v_1, v_1 M, v_1 M^2, \ldots, v_1 M^{d_1})$ is linearly dependent. If

$$v_1 M^{d_1} = \sum_{i=0}^{d_1 - 1} a_i v_1 M^i \quad \text{then} \quad \mathrm{ord}_M(v_1) = x^{d_1} - \sum_{i=0}^{d_1 - 1} a_i x^i.$$

Choose some $v_2 \in V \setminus \langle v_1 \rangle_M$ and find smallest $d_2 \in \mathbb{N}$, such that $(v_1, v_1 M, \ldots, v_1 M^{d_1 - 1}, v_2, v_2 M, \ldots, v_2 M^{d_2})$ is linearly dependent. If

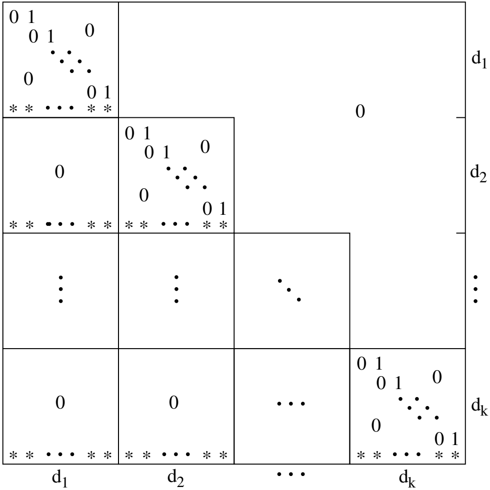
$$v_2 M^{d_2} = \sum_{i=0}^{d_1 - 1} b_i v_1 M^i + \sum_{i=0}^{d_2 - 1} c_i v_2 M^i \quad \text{then}$$

$$\mathrm{ord}_M(v + \langle v_1 \rangle_M) = x^{d_2} - \sum_{i=0} c_i x^i.$$

Going on like this we find an $\mathbb{F}$-basis Y of V:

$$Y := (v_1, v_1 M, \ldots, v_1^{d_1 - 1}, \ldots, v_k, v_k M, \ldots, v_k M_k^{d_k - 1}).$$

The matrix $Y \cdot M \cdot Y^{-1}$



- Block lower-triangular
- with companion matrices along diagonal
- some sparse garbage below the diagonal

The minimal polynomial

$\rightarrow$ compute the absolute order polynomials $\mathrm{ord}_M(v_i)$ instead the relative ones $\mathrm{ord}_M(v_i + \langle v_1, \ldots, v_{i-1} \rangle)_M$.

Lemma (Minimal polynomial)

If $V = \langle v_1, \ldots, v_k \rangle_M$ then

$$\mu_M = \mathrm{lcm}(\mathrm{ord}_M(v_1), \ldots, \mathrm{ord}_M(v_k)).$$

Problem:

- $\dim_{\mathbb{F}}(V_i) - \dim_{\mathbb{F}}(V_{i-1})$ might be small
- even if $\dim_{\mathbb{F}}(V_i)$ is big.

(set $V_i := \langle v_1, \ldots, v_i \rangle_M$)

Characteristic polynomial: asymptotically $\leq 5n^3$ field ops.

Minimal polynomial: asymptotically $\sim n^4$ field ops.

(both worst case analysis)

A Monte Carlo approach

What can we do about it?

Two lemmas

Lemma (Order polynomials in cyclic spaces)

Let $W := \langle v \rangle_M < V$ be a cyclic subspace and $p := \mathrm{ord}_M(v)$ be the order polynomial of v. Let $w = v \cdot q(M) \in W$ with $\deg(q) < \deg(p)$. Then

$$\mathrm{ord}_M(w) = \frac{p}{\gcd(p, q)}.$$

Lemma (Relative and absolute order polynomials)

Let $W < V$ be M-invariant and $v \in V$. If $q := \mathrm{ord}_M(v + W)$ is the relative order polynomial of v, then $v \cdot q(M) \in W$ and

$$\mathrm{ord}_M(v) = q \cdot \mathrm{ord}_M(v \cdot q(M)).$$

Computing order polynomials

We now use the filtration

$$0 = V_0 < V_1 < V_2 < \cdots < V_k = V.$$

Start with $v \in V_j$ for some $1 \leq j \leq k$. Then

- compute $q_j := \mathrm{ord}_M(v + V_{j-1})$ in V_j / V_{j-1} (gcd computation with $\mathrm{ord}_M(v_j + V_{j-1})$),
- evaluate $v_j \cdot q_j(M) \in V_{j-1}$,
- proceed inductively,
- take product $\prod_{i=1}^{j} q_j$.

$\rightarrow$ use sparseness of YMY^{-1} by "thinking in basis Y"

Needs $\leq (j+8) \cdot D^2 + j \cdot D$ field ops. where $D := \dim_{\mathbb{F}}(V_j)$.

A Monte Carlo algorithm

Proposition

Let $\mathbb{F} = \mathbb{F}_q$, randomise $v_1, \ldots, v_u \in V$ independently and uniformly distributed, $\chi_M = \prod_{i=1}^{t} q_i^{e_i}$. Then:

$$\mathrm{Prob}\,(\mathrm{lcm}(\mathrm{ord}_M(v_1), \ldots, \mathrm{ord}_M(v_u)) = \mu_M)$$

is at least $\displaystyle\prod_{i=1}^{t}(1 - q^{-u\deg(q_i)})$.

Algorithm: Input M, $0 < \epsilon < 1/2$

- Compute χ_M, Y, $\mathrm{ord}_M(v_i + V_{i-1})$ for $1 \le i \le k$
- Determine least u, such that probability $> 1 - \epsilon$
- Compute $\mathrm{ord}_M(v_1), \ldots, \mathrm{ord}_M(v_u)$
- Return least common multiple

Needs asymptotically $\le 5n^3 + \mathrm{FACTORISATION}(n)$ field ops.

Back to the example

Baby Monster group $B = \langle a, b \rangle$ with $a, b \in \mathbb{F}_2^{4370 \times 4370}$
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The new algorithm needs

- 13.3 s to compute μ_M with $\epsilon = 1/100$
- 30.0 s with deterministic verification afterwards

How typical is this example?

Irreducible factors of χ_M:

deg	1	1	2	4	6	88	197	854	934
χ_M	2	2277	4	1	1	1	1	1	1
μ_M	1	5	4	1	1	1	1	1	1

What we see is

- typical behaviour for such matrices,
- most matrices are not of this type,
- however, such matrices might occur in applications.