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Relaxing order basis computation

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Context

Let \mathbb{K} be a field, $F = \sum_{i \geq 0} F_i x^i \in \mathbb{K}[[x]]^{m \times n}$ a matrix of power series, σ a positive integer and (F, σ) be the $\mathbb{K}[[x]]$ -module defined by the set of $v \in \mathbb{K}[[x]]^{1 \times m}$ such that $vF \equiv 0 \pmod{x^\sigma}$.

Definition of Order basis: $P \in \mathbb{K}[[x]]^{m \times m}$ is a (left) (σ, \vec{s}) -order basis of F if the rows of P form a \vec{s} -row reduced basis of (F, σ) (see [1]).

Order basis are used in: column reduction [2]; minimal nullspace basis [3]; block Wiedemann algorithm [4]; ...

Two existing algorithms

Input: $F \in \mathbb{K}[[x]]^{m \times n}$, $\sigma \in \mathbb{N}^*$ and $\vec{s} \in \mathbb{Z}^m$

Output: $P \in \mathbb{K}[[x]]^{m \times m}$ a (σ, \vec{s}) -order basis of F and $\vec{u} \in \mathbb{Z}^m$ the shifted \vec{s} -row degree of P .

To simplify the presentation, let us assume w.l.o.g. that:

- the procedure $\text{Basis}(F, \vec{s})$ handles the $(1, \vec{s})$ -order basis case
- $n = O(m)$ and the shift \vec{s} is balanced, as in [2]

M-Basis

Naive algorithm, iterative on the order σ , which costs $O(m^\omega \sigma^2)$ op. in \mathbb{K} .

- ✗ Quadratic complexity in the precision σ
- ✓ Easy to stop at any intermediate step
- ✓ Minimal knowledge on F , only coefficients F_0, \dots, F_k at step k

Algorithm 1: M-Basis(F, σ, \vec{s})

```

1:  $P, \vec{u} := \text{Basis}(F \bmod x, \vec{s})$ 
2: for  $k = 1$  to  $\sigma - 1$  do
3:    $F' := x^{-k} P \cdot F \bmod x^{k+1}$ 
4:    $P_k, \vec{u}_k := \text{Basis}(F', \vec{u})$ 
5:    $P := P_k \cdot P$ 
6: return  $P, \vec{u}$ 

```

PM-Basis

Recursive variant using a divide and conquer strategy on the order σ which costs $O(m^\omega M(\sigma) \log(\sigma)) = O(m^\omega \sigma)$ operations in \mathbb{K} .

- ✓ Quasi-linear complexity in the precision σ
- ✗ Not convenient for early termination
- ✗ Often requires to know coefficients of F in advance

Algorithm 2: PM-Basis(F, σ, \vec{s})

```

1: if  $\sigma = 1$  then
2:   return  $\text{Basis}(F \bmod x, \vec{s})$ 
3: else
4:    $P_1, \vec{u}_1 := \text{PM-Basis}(F, \sigma/2, \vec{s})$ 
5:    $F' := (x^{-\sigma/2} P_1 \cdot F) \bmod x^{\sigma/2}$ 
6:    $P_h, \vec{u}_h := \text{PM-Basis}(F', \sigma/2, \vec{u}_1)$ 
7:   return  $P_h \cdot P_1, \vec{u}_h$ 

```

Our contribution

- Give an algorithm for order basis with the following properties:
 - ✓ **Quasi-optimality:** it takes a quasi-linear time in the precision σ ;
 - ✓ **Early termination:** easy to stop at any intermediate step;
 - ✓ **Relaxed algorithm:** minimal knowledge on the input F at each step.
- Use 1 to improve the complexity of block Wiedemann approach.

Fast iterative algorithm

Iterative-PM-Basis

Iterative version of PM-Basis that regroups computations step by step

- ✓ Quasi-linear complexity in the precision σ
- ✓ Convenient for early termination
- ✗ Often requires to know coefficients of F in advance

Algorithm 3: Iterative-PM-Basis(F, σ, \vec{s})

```

1:  $P_0, \vec{u} := \text{Basis}(F \bmod x, \vec{s})$ 
2:  $P := [P_0]$  and  $S := [0, \dots, 0, F]$  with  $\lceil \log_2(\sigma) \rceil$  zeros
3: for  $k = 1$  to  $\sigma - 1$  do
4:    $\ell := \nu_2(k)$  and  $\ell' := \begin{cases} \lceil \log_2(\sigma) \rceil & \text{if } k = 2^\ell \\ \nu_2(k - 2^\ell) & \text{otherwise} \end{cases}$ 
5:   Merge first  $\ell + 1$  elements of  $P$  by multiplication product tree step 7
6:    $S[\ell + 1] := (x^{-2^\ell} P[1] \cdot S[\ell' + 1]) \bmod x^{2^\ell}$  middle product step 5
7:    $P_k, \vec{u}_k := \text{Basis}(S[\ell + 1] \bmod x, \vec{u})$  recursive leafs step 2
8:   Insert  $P_k$  at the beginning of  $P$ 
9: return  $\prod_i P[i]$ 

```

Relaxing the order basis algorithm

Problem:

At step $k = 2^\ell$, Iterative-PM-Basis requires $S[\lceil \log_2(\sigma) \rceil + 1] \bmod x^{2^{\ell+1}}$, that is $F \bmod x^{2^{\ell+1}}$, to perform the middle product of step 6. However, we only need the middle product modulo x at step k , and therefore $F \bmod x^{1+2^\ell}$. The other coefficients of the middle product will be used in the next steps.

Solution:

Compute the middle products gradually with the additional constraint of not using any coefficient of the input before necessary, *i.e.* using a **relaxed** algorithm.

Definition of relaxed (or on-line) algorithm:

When computing the coefficient in x^k of the output, a *relaxed* algorithm can read at most the coefficients in $1, \dots, x^k$ of the input.

Relaxed middle product

Two methods for a relaxed middle product algorithm:

- Compute a full $2n \times n$ product using a relaxed multiplication algorithm on polynomial of matrices ([5])
- Compute just the middle product as in Figure 1 to gain asymptotically a factor 2 compared to method 1.

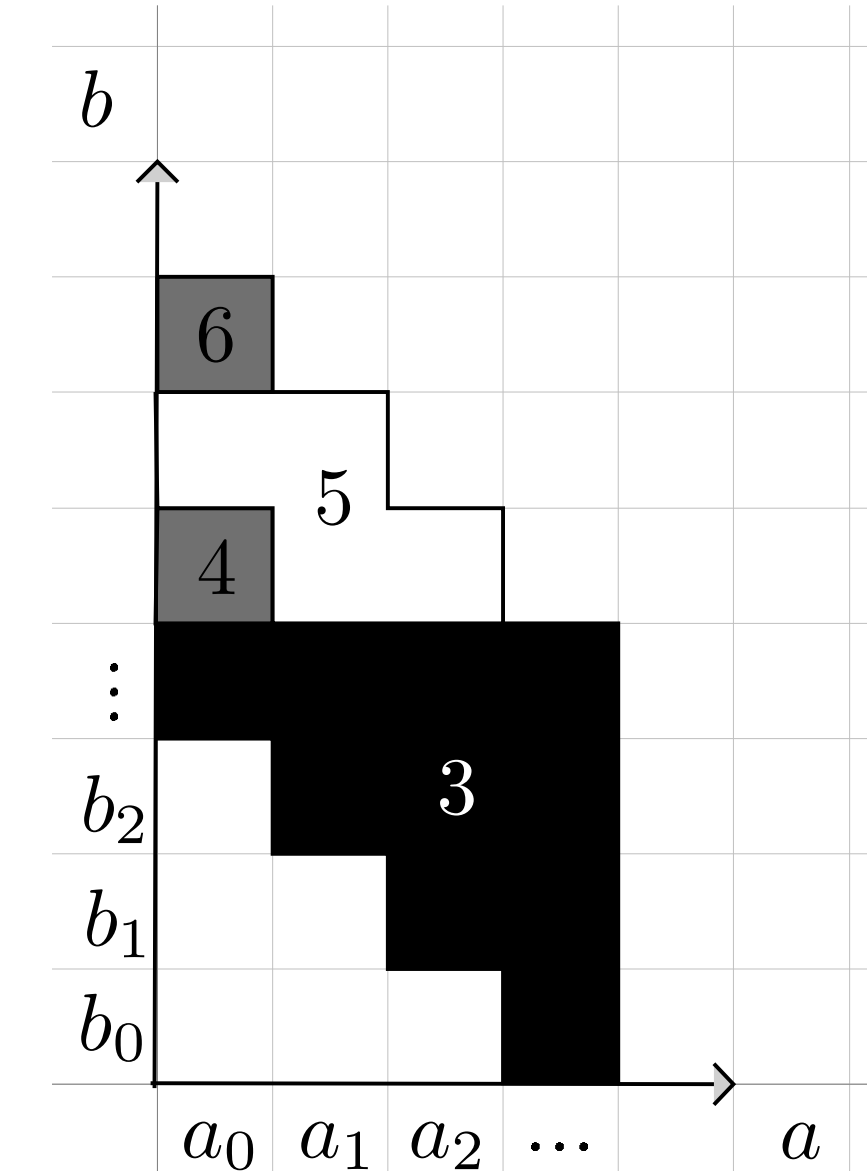


Figure 1: Relaxed middle product

Relaxed-PM-Basis

Using this relaxed middle product within Iterative-PM-Basis, we obtain a new order basis algorithm relaxed w.r.t. F , which costs $O(k^\omega M(\sigma) \log^2(\sigma))$.

- ✓ Quasi-linear complexity in the precision σ (with an extra $\log_2(\sigma)$)
- ✓ Convenient for early termination
- ✓ Requires minimal knowledge on F

Application to block Wiedemann algorithm

Let $A \in \text{GL}_N(\mathbb{K})$ with $O(N)$ non-zero elements and $S = \sum_{i \in \mathbb{N}} U A^i V x^i$ for random $U, V^T \in \mathbb{K}^{n \times N}$. The block Wiedemann approach uses a (σ, \vec{s}) -order basis of $F = [S^T \mid I_n]^T \in \mathbb{K}[[x]]^{2n \times n}$ to solve sparse linear systems $Ay = b$.

Current approach:

Computing S at precision σ costs $O(n^{\omega-1} N \sigma)$ operations in \mathbb{K} , which is dominant since $n \ll N$. An *a priori* bound δ on the order σ is hard to find or may be loose. To circumvent this the paper [6] proposes a stopping criteria which has to be integrated into an iterative algorithm.

Benefits of our approach:

- Iterative-PM-Basis provides the first iterative algorithm with quasi-linear time complexity that can use stopping criteria from [6].
- Relaxed-PM-Basis improves the complexity of 1 on average by a constant factor because less coefficients of S need to be computed.

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