On Affine Tropical F5 Algorithms

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ABSTRACT

Let K be a field equipped with a valuation. Tropical varieties over K can be defined with a theory of Gröbner bases taking into account the valuation of K. Because of the use of the valuation, the theory of tropical Gröbner bases has proved to provide settings for computations over polynomial rings over a p-adic field that are more stable than that of classical Gröbner bases.

Beforehand, these strategies were only available for homogeneous polynomials. In this article, we extend the F5 strategy to a new definition of tropical Gröbner bases in an affine setting.

We provide numerical examples to illustrate time-complexity and p-adic stability of this tropical F5 algorithm. We also illustrate its merits as a first step before an FGLM algorithm to compute (classical) lex bases over p-adics.

CCS CONCEPTS

•**Computing methodologies → Algebraic algorithms;**

GENERAL TERMS

Algorithms, Theory

KEYWORDS

Algorithms, Tropical geometry, Gröbner bases, F5 algorithm, p-adic precision

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1 INTRODUCTION

Tropical geometry as we understand it has not yet reached half a century of age. It has nevertheless spawned significant applications to very various domains, from algebraic geometry to combinatorics, computer science, economics, non-archimedean geometry (see [MS15], [EKL06]) and even attempts at proving the Riemann hypothesis (see [C15]).

Effective computation over tropical varieties make decisive use of Gröbner bases. Since Chan and Maclagan's definition of tropical Gröbner bases taking into account the valuation in [C13, CM13], computations of tropical Gröbner bases are available over fields with trivial or non-trivial valuation, but only in a context of homogeneous ideals.

On the other hand, for classical Gröbner bases, numerous algorithms have been developed allowing for more and more efficient computations. The latest generation of algorithms for computing Gröbner bases is the family of signature-based algorithms, which keep track of where the polynomials come from in order to anticipate useless reductions. This idea was initiated in Algorithm F5 [F02], and has since then been widely studied and generalized ([BFS14, EF17]).

Most of those algorithms, including the original F5 algorithm, are specifically designed for homogeneous systems, and adapting them to affine (or inhomogeneous) systems requires special care (see [E13]).

An F5 algorithm computing tropical Gröbner bases without any trivial reduction to 0, inspired by the classical F5 algorithm, has been described in [VY17]. The goal of this paper is to extend the definition of tropical Gröbner bases to inhomogeneous ideals, and describe ways to adapt the F5 algorithm in this new setting.

The core motivation is the following. It has been proved [V15] that computing tropical Gröbner bases, taking into account the valuation, is more stable for polynomial ideals over a p-adic field than classical Gröbner bases.

Thus, an affine variant of tropical Gröbner bases is highly desirable to handle non-homogeneous ideals over p-adics. For classical Gröbner bases, it is always possible to homogenize the input ideal, compute a homogeneous Gröbner basis, and dehomogenize the result. This technique is not always optimal, because the algorithm may end up reaching a higher degree than needed, computing points at infinity of the system, but it always gives a correct result and, in the case of signature Gröbner basis algorithms, is able to eliminate useless reductions. However, in a tropical setting, terms are ordered with a tropical term order, taking into account the valuation of the coefficients. As far as we know it, there is no way to dehomogenize a system in a way that would preserve the tropical term order. Indeed, no tropical term order can be an elimination order.

Moreover, the FGLM algorithm can be adapted to the tropical case (see Chap. 9 of [V15]), making it possible to compute a lexicographical (classical) Gröbner basis from a tropical one. We provide numerical data to get an idea on the loss in precision for the computation of a lex Gröbner basis using a tropical F5 algorithm followed by an FGLM algorithm, in an affine setting.

1.1 Related works

A canonical reference for an introduction to computational tropical algebraic geometry is the book of Maclagan and Sturmfels [MS15].

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The computation of tropical varieties over $\mathbb{Q}$ with trivial valuation is available in the Gfan package by Anders Jensen (see [Gfan]), by using standard Gröbner bases computations. Chan and Maclagan have developed in [CM13] a Buchberger algorithm to compute tropical Gröbner bases for homogeneous entry polynomials (using a special division algorithm). Following their work, still for homogeneous polynomials, a Matrix-F5 algorithm has been proposed in [V15] and a Tropical F5 algorithm in [VY17]. Markwig and Ren have provided a completely different technique of computation using projection of standard bases in [MY16], again only for homogeneous entry polynomials.

In the classical Gröbner basis setting, many techniques have been studied to make the computation of Gröbner bases more efficient. In particular, Buchberber's algorithm is frequently made more efficient by using the *sugar-degree* (see [GMNRT91, BCM11]) instead of the actual degree for selecting the next pair to reduce. This technique was a precursor of modern signature techniques, in the sense that the sugar-degree of a polynomial is exactly the degree of its signature. General signature-based algorithms for computing classical Gröbner bases of inhomogeneous ideals have been extensively studied in [E13].

1.2 Specificities of computating tropical GB

The computation of tropical GB, even by a Buchberger-style algorithm, is not as straightforward as for classical Gröbner bases. One way to understand this is the following: even for homogeneous ideals, there is no equivalence between tropical Gröbner bases and row-echelon linear bases at every degree. Indeed,we can remark that $(f_1, f_2) = (x + y, 2x + y)$ is a tropical GB over $\mathbb{Q}[x, y]$ with 2-adic valuation, $w = [0, 0]$ and grevlex ordering. Nevertheless, the corresponding 2×2 matrix in the vector space of homogeneous polynomials of degree 2 is not under tropical row-echelon form.

As a consequence, reduction of a polynomial by a tropical GB is not easy. In [C13, CM13], Chan and Maclagan relied on a variant of Mora's tangent cone algorithm to obtain a division algorithm. In [V15, VY17], the authors relied on linear algebra and the computation of (tropical) row-echelon form. In this article, we extend their method to the computation of tropical Gröbner bases in an affine setting, through an F5 algorithm.

1.3 Main idea and results

Extending the tropical F5 algorithm to inhomogeneous inputs poses two difficulties. First, as mentioned, tropical Gröbner bases used to be only defined and computed for homogeneous systems. Even barebones algorithms such as Buchberger's algorithm are not available for inhomogeneous systems. The second problem is a general problem of signature Gröbner bases with inhomogeneous input. The idea of signature algorithms is to compute polynomials with increasing signatures, whereas the F5 criterion detects trivial reductions to 0 by matching candidate signatures with existing leading terms. For homogeneous ideals, the degree of the signature of a polynomial and the degree of the polynomial itself are correlated. This is what makes the F5 criterion applicable.

The survey paper [E13] has shown that Algorithm F5, using the *position over term* ordering on the signatures, has to reach a tradeoff between eliminating all reductions to 0 and performing other useless reductions.

More precisely, let $f_1, \dots, f_m$ be inhomogeneous polynomials with coefficients in a field with valuation K, and define $I_{k,d}$ the vector space of polynomials in $\langle f_1, \dots, f_k \rangle$ with degree at most d. With the usual computational strategy, the algorithm computes a basis of $I_{1,1}$, then $I_{2,1}$, and so on until $I_{m,1}$, and then $I_{1,2}$, and so on. In a lot of situations [BFS04] ideals with more generators have a Gröbner basis with lower degree, and this strategy ensures that the algorithm does not reach a degree higher than needed.

However, the same algorithm for affine system will, at each step, merely compute a *set of polynomials* in each $I_{k,d}$. This set needs not be a generating set because of degree falls. To obtain a basis instead, one has to proceed up to some $I_{k,\delta}$ with $\delta \geq d$. When $\delta > d$, some polynomials will be missing for the F5 criterion in degree less than δ, and the corresponding trivial reductions to 0 will not be eliminated.

In this paper, we show that the tropical F5 algorithm [VY17] works in an affine setting, and we caracterize those trivial reductions to 0 which are eliminated by the F5 criterion. In particular, we show that the Macaulay matrices built at each step of the computations are Macaulay matrices of all polynomials with a given *sugar-degree*.

Compared to [VY17], the overall presentation of the F5 algorithms is clarified. It can now be summarized as the following strategy: filtration, signature, F5 elimination criterion, Buchberger-F5 criterion and finally the F5 algorithm.

Theorem 1.1. *Given a set of (non-necessarily homogeneous) polynomials $f_1, \dots, f_m \in K[X_1, \dots, X_n]$, the Tropical F5 algorithm (Algorithm 3) computes a tropical Gröbner basis of I, without reducing to 0 any trivial tame syzygy (Def. 3.1).*

We also examine an incremental affine version of the homogeneous tropical F5-algorithm and an affine tropical F4, and we compare their performances on several examples. Even in a non-homogeneous setting, the loss in precision of the tropical F5 algorithm remains satisfyingly low.

1.4 Organization of the paper

Section 2 introduces notations and nonhomogeneous tropical Gröbner bases. Section 3 then introduces the filtration on ideals necessary for F5 algorithms in this context. Section 4 is devoted to provide a Buchberger-F5 criterion on which Section 5 elaborates a first tropical F5 algorithm. Section 6 briefly presents other methods for the computation of nonhomogeneous tropical Gröbner bases. Finally, Section 7 displays numerical results related to the precision behaviour and time-complexity of the algorithms we have described.

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2 AFFINE TROPICAL GB

2.1 Notations

Let k be a field with valuation val. The polynomial ring $k[X_1, \dots, X_n]$ will be denoted by A. Let T be the set of monomials of A. For $u = (u_1, \dots, u_n) \in \mathbb{Z}_{\geq 0}^n$, we write x^u for $X_1^{u_1} \dots X_n^{u_n}$ and $|f|$ for the degree of $f \in A$.

The matrix of a list of polynomials written in a basis of monomials is called a *Macaulay matrix*.

Given a mapping $\phi : U \to V$, $Im(\phi)$ denote the image of ϕ. For a matrix M, $Rows(M)$ is the list of its rows, and $Im(M)$ denotes the left-image of M (*n.b.* $Im(M) = span(Rows(M))$). For $w \in Im(val)^n \subset \mathbb{R}^n$ and $\leq_1$ a monomial order on A, we define $\leq$ a tropical term order as in the following definition:

Definition 2.1. Given $a, b \in k^*$ and x^α and x^β two monomials in A, we write $ax^\alpha < bx^\beta$ if:

- $|x^\alpha| < |x^\beta|$, or
- $|x^\alpha| = |x^\beta|$ and $val(a) + w \cdot \alpha > val(b) + w \cdot \beta$, or
- $val(a) + w \cdot \alpha = val(b) + w \cdot \beta$ and $x^\alpha <_1 x^\beta$.

For u of valuation 0, we write $ax^\alpha =_{\leq} uax^\alpha$. Accordingly, $ax^\alpha \leq bx^\beta$ if $ax^\alpha < bx^\beta$ or $ax^\alpha =_{\leq} bx^\beta$.

Throughout this article, we are interested in computing a tropical Gröbner basis of $I = \langle f_1, \dots, f_s \rangle$ for some given $f_1, \dots, f_s \in A$ (ordered increasingly by degree).

2.2 Tropical GB

A tropical term order provides an order on the terms of the polynomials $f \in A$.

Definition 2.2. For $f \in A$, we define $LT(f)$ to be the biggest term of f. We define $LM(f)$ to be the monomial corresponding to $LT(f)$ and $LC(f)$ the corresponding coefficient.

We define $LM(I)$ to be the monomial ideal generated by the monomials $LM(f)$ for $f \in I$.

We can then naturally define what is a tropical Gröbner bases (*tropical GB* for short):

Definition 2.3. $G \subset I$ is a tropical GB of I if span($LM(g)$ for $g \in G$) $= LM(I)$.

We can remark that for homogeneous polynomials this definition coincide with that given in [VY17].

3 FILTRATION AND $\mathfrak{S}$-GB

3.1 Definition and elimination criterion

One of the main ingredient for F5 algorithms is the definition of a vector space filtration of the ideal I. It is defined from the initial polynomials $F = (f_1, \dots, f_s)$ generating I.

First, we extend the monomial ordering $\leq$ on A to the vector space A^s.

To that intent, we highlight some monomials that appear as leading monomial of a syzygy.

Definition 3.1. Let $(a_1, \dots, a_s) \in A^s$ be such that:

(1) $\sum_j a_j f_j = 0$.
(2) $a_i \neq 0$ and $a_j = 0$ for $j > i$.
(3) for all $j < i$, $|a_j f_j| \leq |a_i f_i|$.

We call such a syzygy a tame syzygy and we define $LM(a_i)e_i$ to be its leading monomial. We define $LM_m(TSyz(F))$ as the module in A^s generated by the leading monomials of the tame syzygies.

The F5 criterion that we use in this article is designed to recognize some of the tame syzygies and use this knowledge to avoid useless reduction to zero of some polynomials. It is the main motivation for defining a filtration on the vector space A^s. We use a degree-refining monomial ordering $\leq_m$ on A.[1] We define a total order on the monomials of A^s.

Definition 3.2. We write that $x^\alpha e_i \leq_{sign} x^\beta e_j$ if:

(1) if $i < j$
(2) if $i = j$ and $|x^\alpha f_i| < |x^\beta f_j|$.
(3) if $i = j$ and $|x^\alpha f_i| = |x^\beta f_j|$, and
  - $x^\alpha \notin LM(TSyz(F))$ and $x^\beta \in LM(TSyz(F))$.
  - both $x^\alpha, x^\beta \in LM(TSyz(F))$ and $x^\alpha \leq_m x^\beta$.
  - both $x^\alpha, x^\beta \notin LM(TSyz(F))$ and $x^\alpha \leq_m x^\beta$.

Definition 3.3. We consider the vector space

$$I_{\leq_{sign} x^\alpha e_i} := Span(\{x^\beta f_j, \text{ s.t. } x^\beta e_j \leq_{sign} x^\alpha e_i\})$$

and the vector space $I_{<_{sign} x^\alpha e_i}$ defined accordingly. We define $I = \bigcup_{\uparrow x^\alpha e_i} I_{\leq_{sign} x^\alpha e_i}$ as an increasing vector space filtration of I.

We then have a very natural definition of signature. In litterature, this notion of signature is sometimes called *minimal signature*.

Definition 3.4. For $f \in I$, the smallest $x^\alpha e_i$ such that $f \in I_{\leq_{sign} x^\alpha e_i}$ is called the **signature** of f and noted $S(f)$.

The degree $|x^\alpha f_i|$ is called the **sugar-degree** of $x^\alpha e_i$.[2] For the purpose of Algorithm 3, we design a filtration compatible with the sugar-degree.

Definition 3.5. We consider the vector space

$$I^{\leq d} = Span(\{x^\beta f_j, \text{ s.t. } |x^\beta e_j| \leq d\})$$

We then define, for $x^\alpha e_i$ of sugar-degree d, the vector space $I^{\leq d}_{\leq_{sign} x^\alpha e_i} = Span(\{x^\beta f_j, \text{ s.t. } x^\beta e_j \leq_{sign} x^\alpha e_i \text{ and } |x^\beta f_j| \leq d\})$.

$I = \bigcup_{\uparrow d} I^{\leq d}$ is also a vector space filtration. $I^{\leq d}$ can itself be filtrated by the $I^{\leq d}_{\leq_{sign} x^\alpha e_i}$. We have a compatible notion of signature:

Definition 3.6. For $d \in \mathbb{Z}_{>0}$ and $f \in I^{\leq d}$, the smallest $x^\alpha e_i$ such that $f \in I^{\leq d}_{\leq_{sign} x^\alpha e_i}$ is called the d-**signature** of f and noted $S_d(f)$.

We remark that $S_d(f)$ can be different from $S(f)$ for small f, but all $S_d(f)$ are equal when d is large.

The main motivation for defining the vector spaces $I^{\leq d}_{\leq_{sign} x^\alpha e_i}$ is their finite dimension. Their compatibility with the sugar-degree allows the F5 algorithm to compute with only one Macaulay matrix by sugar-degree d.

The goal of the F5 criterion is to recognize some $x^\alpha e_i$ such that the filtration is constant at $I^{\leq d}_{\leq_{sign} x^\alpha e_i}$. As a consequence, this knowledge allows to skip some calculation as, because of this constancy, they will not provide any new leading monomial. We can then state a first version of the F5 elimination criterion:

Proposition 3.7 ([F02]). *If x^α is such that $x^\alpha e_i \in LM(Tsyz(F))$, $d \geq |x^\alpha f_i|$, then the filtration is constant at $I^{\leq d}_{\leq_{sign} x^\alpha e_i}$. If $x^\alpha \in LM(I^{\leq d}_{\leq_{sign} x^\beta e_j})$ for some x^β and j such that $|x^\beta f_j| \leq |x^\alpha|$, then $x^\alpha e_i \in LM(Tsyz(F))$ for any $i > j$.*

[1] $\leq_m$ is not necessarily related to $\leq_1$ and $\leq$.
[2] Sugar-degree has been introduced and explored in [GMNRT91, BCM11].

Proof. For the first part, we can write $(x^\alpha + g)f_i = \sum_{j<i} a_j f_j$, with $LT(g) < x^\alpha$ and for all $j < i$, $|a_j f_j| \leq |x^\alpha f_i|$. Then:

$$x^\alpha f_i = (-g)f_i + \sum_{j=1}^{i-1}(a_j f_i)f_j.$$

By linear algebra and a complete reduction using as pivot the $x^\beta e_j \in LM(Tsyz(F))$, we can assume that g has no monomial in $LM(TSyz(F))$ and obtain: $x^\alpha f_i \in I^{\leq d}_{<x^\alpha e_i}$, and therefore, the filtration is constant at $I^{\leq d}_{\leq x^\alpha e_i}$.

For the second part, we can write $x^\alpha + g = \sum_{k\leq j} a_k f_k$, with $LT(g) < x^\alpha$ and for all $k \leq j$, $|a_j f_j| \leq |x^\beta f_j| \leq |x^\alpha|$. Then $(x^\alpha + g)f_i - \sum_{k\leq j}(a_k f_i)f_k = 0$ and we do have $|x^\alpha f_i| \geq |(a_k f_i)f_k|$ for all $k \leq j$. □

If all the f_i's are homogeneous, this coincides with the usual F5 elimination criterion, as for example stated in [VY17], which eliminates all trivial reductions to zero in the course of the algorithm. For affine polynomials, the F5 criterion only eliminates those trivial reductions which are tame.

3.2 Tropical $\mathfrak{S}$-GB

In order to take advantage of the F5 elimination criterion to compute tropical Gröbner bases, we focus on the computation of tropical Gröbner bases that are compatible with the filtration: tropical $\mathfrak{S}$-GB. We need first the definition of reductions compatible with the filtration and the corresponding irreducible polynomials.

Definition 3.8 ($\mathfrak{S}$-reduction)**.** Let $e, g \in I$, $h \in I$. We say that e $\mathfrak{S}$**-reduces** to g with h, $e \to^h_{\mathfrak{S}} g$, if there are $t \in T$ and $\alpha \in k^*$ such that:

- $LT(g) < LT(e)$, $LM(g) \neq LM(e)$ and $e - \alpha t h = g$ and
- $S(th) <_{sign} S(e)$.

It is then natural to define what is an $\mathfrak{S}$-irreducible polynomial.

Definition 3.9 ($\mathfrak{S}$-irreducible polynomial)**.** We say that $g \in I$ is $\mathfrak{S}$-irreducible if there is no $h \in I$ which $\mathfrak{S}$-reduces g. If there is no ambiguity, we might omit the $\mathfrak{S}-$.

Definition 3.10 (Tropical $\mathfrak{S}$-Gröbner basis)**.** We say that $G \subset I$, a set of $\mathfrak{S}$-irreducibles polynomials, is a **tropical $\mathfrak{S}$-Gröbner basis** (or tropical $\mathfrak{S}$–GB, or just $\mathfrak{S}$–GB for short when there is no ambiguity) of I with respect to a given tropical term order if for each $\mathfrak{S}$-irreducible polynomial $h \in I$, there exist $g \in G$ and $t \in T$ such that $LM(tg) = LM(h)$ and $tS(g) = S(h)$.

Definitions 3.8, 3.9 and 3.10 have natural analogues when one restricts to the vector space $I^{\leq d}$ and S_d.

Proposition 3.11. *If G is a tropical $\mathfrak{S}$-Gröbner basis, then for any nonzero $h \in I$, there exist $g \in G$ and $t \in T$ such that:*

- *$LM(tg) = LM(h)$*
- *$S(tg) = tS(g) = S(h)$ if h is irreducible, and $S(tg) = tS(g) <_{sign} S(h)$ otherwise.*

Hence, there is an $\mathfrak{S}$-reductor for h in G when h is not irreducible.

Corollary 3.12. *If G is a tropical $\mathfrak{S}$-Gröbner basis, then G is a tropical Gröbner basis of I, for $<$.*

As a consequence computing a tropical $\mathfrak{S}$-GB provides a tropical GB, and we can use the F5 elimination criterion 3.7 to our advantage when computing these tropical $\mathfrak{S}$-GB. Moreover, we also have the following finiteness result:

Proposition 3.13. *Every tropical $\mathfrak{S}$-Gröbner basis contains a finite tropical $\mathfrak{S}$-Gröbner basis.*

Proof. We refer to the proof of Proposition 14 of [AP]. It uses an adapted Dickson's Lemma and since it is mostly a question of monomial ideals, the transposition to the tropical setting is direct. □

3.3 Linear algebra and existence

For $x^\alpha \in T$ and $1 \leq i \leq n$, let us denote by $Mac_{\leq_{sign} x^\alpha e_i}(F)$ the Macaulay matrix of the polynomials $x^\beta f_j$ such that $x^\beta f_j \leq x^\alpha f_i$, ordered increasingly for the order on the $x^\beta e_j$'s. One can perform a tropical LUP algorithm on $Mac_{\leq d}(F)$ (see Algo. 2) and obtain all the leading monomials in $I_{\leq_{sign} x^\alpha e_i}$. This can be (theoretically) performed for all $x^\alpha e_i$ to obtain the existence of an $\mathfrak{S}$-GB of I.

3.4 More on signatures

We define Σ to be the set of signatures.

Thanks to Proposition 3.7, not all $x^\alpha e_i$ can be a signature:

Remark 3.14. If $x^\alpha e_i \in LM(TSyz(F))$ then $x^\alpha e_i \notin \Sigma$.

We provide two lemmata to understand the compatibility of Σ with basic operations on polynomials.

Lemma 3.15. *If $f, g \in I$ are such that $S(f) = S(g)$ and $LM(f) \neq LM(g)$, then there exists $a, b \in k^\times$ such that $S(af + bg) < S(f)$ and $af + bg \neq 0$.*

If one takes the point of view of linear algebra, the proof is direct.

Lemma 3.16. *If $g \in I$ and $\tau \in T$ then $S(\tau g) \leq \tau S(g)$. If moreover $\tau S(g) \in \Sigma$, then $S(\tau g) = \tau S(g)$ and for all $\mu \in T$ such that μ divides τ, $S(\mu g) = \mu S(g)$.*

Proof. The first part is direct. For the second part, one can show that it is possible to write that $\tau g = h + r$ for some $h \in I$ of signature $\tau S(g)$, irreducible, and $r \in I_{<_{sign} \tau S(g)}$ and conclude that $S(\tau g) = \tau S(g)$.

For the last statement, assume that there exists a $\mu \in T$ dividing τ such that $S(\mu g) < \mu S(g)$. Then $S(\tau g) = S(\frac{\tau}{\mu}\mu g) \leq \frac{\tau}{\mu} S(\mu g) < \frac{\tau}{\mu}\mu S(g) = \tau S(g)$, which is a contradiction. □

4 BUCHBERGER-F5 CRITERION

In this section, we explain a criterion, the Buchberger-F5 criterion, on which we build our F5 algorithm to compute tropical $\mathfrak{S}$-Gröbner bases. It is an analogue of the Buchberger criterion which includes the F5 elimination criterion.

We need a slightly different notion of S-pairs, called here normal pairs and can then enounce the Buchberger-F5 criterion.

Definition 4.1 (Normal pair)**.** Given $g_1, g_2 \in I$, let $Spol(g_1, g_2) = u_1 g_1 - u_2 g_2$ be the S-polynomial of g_1 and g_2, with for $i \in \{1, 2\}$, $u_i = \frac{lcm(LM(g_1), LM(g_2))}{LT(g_i)}$. We say that (g_1, g_2) is a **normal pair** if:

(1) the g_i's are $\mathfrak{S}$-irreducible polynomials.
(2) $S(u_i g_i) = LM(u_i)S(g_i)$ for $i = 1, 2$.

(3) $S(u_1 g_1) \neq S(u_2 g_2)$.

Theorem 4.2 (Buchberger-F5 criterion). *Suppose that G is a finite set of $\mathfrak{S}$-irreducible polynomials of $I = \langle f_1, \ldots, f_s \rangle$ such that:*

(1) for all $\forall i \in [\![1, s]\!]$, there exists $g \in G$ such that $S(g) = e_i$.
(2) for any $g_1, g_2 \in G$ such that (g_1, g_2) is a normal pair, there exists $g \in G$ and $t \in T$ such that tg is $\mathfrak{S}$-irreducible and $tS(g) = S(tg) = S(Spol(g_1, g_2))$.

Then G is a $\mathfrak{S}$-Gröbner basis of I.

Remark 4.3. The converse result is clearly true.

Theorem 4.2 is an analogue of the Buchberger criterion for tropical $\mathfrak{S}$-Gröbner bases. To prove it, we adapt the classical proof of the Buchberger criterion and the proof of the tropical Buchberger algorithm of Chan and Maclagan (Algorithm 2.9 of [C13]). We need two lemmata, the first one being elementary.

Lemma 4.4. *Let $x^\alpha, x^\beta, x^\gamma, x^\delta \in T$ and $P, Q \in A$ be such that $LM(x^\alpha P) = LM(x^\beta Q) = x^\gamma$ and $x^\delta = lcm(LM(P), LM(Q))$. Then*

$$Spol(x^\alpha P, x^\beta Q) = x^{\gamma - \delta} Spol(P, Q).$$

Lemma 4.5. *Let G be an $\mathfrak{S}$-Gröbner basis of I up to some signature σ. Let $h \in I$, be such that $S(h) \leq \sigma$. Then there exist $r \in \mathbb{N}$, $g_1, \ldots, g_r \in G$, $Q_1, \ldots, Q_r \in A$ such that for all i and x^α a monomial of Q_i, $S(x^\alpha g_i) = x^\alpha S(g_i) \leq S(h)$ and $LT(Q_i g_i) \leq LT(h)$, the $x^\alpha S(g_i)$'s are all distinct and non-zero, and, finally, we have*

$$h = \sum_{i=1}^{r} Q_i g_i.$$

Proof. It is clear by linear algebra. One can form a Macaulay matrix whose rows correspond to polynomials $c\tau g$ with $\tau \in T, c \in k^\times, g \in G$ such that $S(\tau g) = \tau S(g) \leq S(h)$. Only one row is possible per non-zero signature, and each monomial in $LM(I_{\leq \sigma})$ is reached as leading term by only one row. It is then enough to stack h at the bottom of this matrix and perform a tropical LUP form computation (see Algorithm 2) to read the Q_i's on the reduction of h. □

PROOF of Theorem 4.2. We prove this result by induction on the signature. We follow the order $\leq_{sign}$ for the induction. It is clear for $\sigma = e_1$ and also for the fact we can pass from an $\mathfrak{S}$-GB up to $<_{sign} e_i$ to $\leq_{sign} e_i$. We write the elements of G as $g_1, \ldots, g_r$ for some $r \in \mathbb{Z}_{>0}$.

Let us assume that G is an $\mathfrak{S}$-GB up to signature $<_{sign} \sigma$ for some signature σ and let us prove it is up to $\leq_{sign} \sigma$. We can assume that all $g \in G$ satisfy $LC(g) = 1$. Let $P \in I$ be irreducible, with $LC(P) = 1$ and such that $S(P) = \sigma$. We prove that there is $\tau \in T, g \in G$ such that $LM(P) = LM(\tau g)$ and $S(\tau g) = \tau S(g) = \sigma$.

Our first assumption for G implies that there exist at least one $g \in G$ and some $\tau \in T$ such that $\tau S(g) = S(P) = \sigma$.

If $LM(\tau g) =_{\leq} LM(P)$ we are done. Otherwise, by Lemma 3.15, there exist some $a, b \in k^*$ such that $S(aP + b\tau g) = \sigma'$ for some $\sigma' <_{sign} \sigma$.

We can apply Lemma 4.5 to $aP + b\tau g$ and obtain that there exist $h_1, \ldots, h_r \in A$, such that $P = \sum_{i=1}^{r} h_i g_i$, and for all i, and x^γ monomial of h_i, the $x^\gamma S(g_i) = S(x^\gamma g_i) \leq_{sign} \sigma$ are all distincts. We remark that $LT(P) \leq \max_i(LT(g_i h_i))$. We denote by $m_i := LT(g_i h_i)$.

Among all such possible ways of writing P as $\sum_{i=1}^{r} h_i g_i$, we define β as the **minimum** of the $\max_i(LT(g_i h_i))$'s. Such a β exists thanks to Lemma 2.10 in [CM13] (adaptation to the non-homogeneous setting is for free). We write $x^u = LM(\beta)$.

If $LT(P) =_{\leq} \beta$, then we are done. Indeed, there is then some i and τ in the terms of h_i such that $LM(\tau g_i) = LM(P)$ and $S(\tau g_i) = \tau S(g_i) \leq_{sign} \sigma$.

We now show that $LT(P) < \beta$ leads to a contradiction.

We can renumber the g_i's so that:

- $\beta =_{\leq} m_1 =_{\leq} \cdots =_{\leq} m_d$.
- $\beta > m_i$ for $i > d$.

We can assume that among the set of possible $(h_1, \ldots, h_r)$ that reaches β, we take one such that this d is minimal.

Since $LT(P) < \beta$, then we have $d \geq 2$.

We can write

$$Spol(g_1, g_2) = LC(g_2) \frac{lcm(LM(g_1), LM(g_2))}{LM(g_1)} g_1 - LC(g_1) \frac{lcm(LM(g_1), LM(g_2))}{LM(g_2)} g_2.$$

By construction, $LM(h_1)S(g_1) \neq LM(h_2)S(g_2)$, so $(LM(h_1)g_1, LM(h_2 g_2)$ is a normal pair. By Lemma 4.4, there exists a term μ such that $\mu \frac{lcm(LM(g_1), LM(g_2))}{LM(g_i)} = LM(h_i)$ for $i\{1, 2\}$. So by Lemma 3.16, (g_1, g_2) is a normal pair as well.

If $S(Spol(g_1, g_2)) = \sigma$, by the second property of the F5 criterion, we are done.

Otherwise, $S(Spol(g_1, g_2)) <_{sign} \sigma$. Moreover, let

$$L = \frac{LC(h_1 g_1)}{LC(g_1)LC(g_2)} \frac{x^u}{lcm(LM(g_1), LM(g_2))}.$$

Then we have $S(L \cdot Spol(g_1, g_2)) \leq_{sign} \sigma$ thanks to 4.4. Using the same construction as before with the first assumption of the F5 criterion and Lemmata 3.15 and 4.5, we obtain some h_i''s such that $L \cdot Spol(g_1, g_2) = \sum_{i=1}^{r} h_i' g_i$, $LT(h_i' g_i) \leq LT(L \cdot Spol(g_1, g_2)) < \beta$ for all i. Furthermore, the signatures $S(x^\alpha g_i) = x^\alpha S(g_i)$ for $i \in \{1, \ldots, r\}$ and x^α in the support of h_i' are all distincts.

We then get:

$$\begin{aligned} P &= \sum_{i=1}^{r} h_i g_i, \\ &= \sum_{i=1}^{r} h_i g_i - L \cdot Spol(g_1, g_2) + \sum_{i=1}^{r} h_i' g_i, \\ &= \left(h_1 - \frac{LC(h_1 g_1)}{LC(g_1)} \frac{x^u}{LM(g_1)} + h_1' \right) g_1 \\ &\quad + \left(h_2 - \frac{LC(h_1 g_1)}{LC(g_2)} \frac{x^u}{LM(g_2)} + h_2' \right) g_2 + \sum_{i=3}^{r} \left(h_i + h_i' \right) g_i, \\ &=: \sum_{i=1}^{r} \widetilde{h}_i g_i, \end{aligned}$$

where the $\widetilde{h}_i$'s are defined naturally.

By construction, $LT(\widetilde{h}_1 g_1) < LT(h_1 g_1) = \beta$ and $LT(\widetilde{h}_i) \leq \beta$ for $i \leq d$ and $LT(\widetilde{h}_i) < \beta$ for $i > d$.

As a consequence, we have obtained a new expression for f with either $max_i(LT(\widetilde{h}_i)) < \beta$ or this term attained stricly less than d times, which is in either case a contradiction with their definitions as minima. So $LT(P) =_{\leq} \beta$, which concludes the proof. □

This theorem holds for $\mathfrak{S}$-GB up to a given signature. We have the following variant as a corollary for compatibility with sugar-degree:

Proposition 4.6. *Suppose that $d \in \mathbb{Z}_{>0}$, and G is a finite set of polynomials of I such that:*

(1) *Any $g \in G$ is $\mathfrak{S}$-irreducible in $I^{\leq d}$.*
(2) *$\forall g1, g_2 \in G$ we have g_1, g_2 and $Spol(g_1, g_2)$ in $I^{\leq d}$.*
(3) *for all $\forall i \in [\![1, s]\!]$, there exists $g \in G$ such that $S_d(g) = e_i$.*
(4) *for any $g_1, g_2 \in G$ such that (g_1, g_2) is a normal pair, there exists $g \in G$ and $t \in T$ such that tg is $\mathfrak{S}$-irreducible and $tS_d(g) = S_d(tg) = S_d(Spol(g_1, g_2))$.*

Then G is a $\mathfrak{S}$-Gröbner basis of I.

5 F5 ALGORITHM

In this section, we present our F5 algorithm. To this intent, we need to discuss some crucial algorithmic points: how to recognize which pairs to proceed and how to build the Macaulay matrices and reduce them.

5.1 Admissible pairs and guessed signatures

The second condition in the Definition 4.1 of normal pairs is not possible to check in advance in an F5 algorithm. One needs an S-Gröbner basis up to the corresponding signature to be able to certify it. To circumvent this issue, we use the weaker notion of admissible pair.

Definition 5.1 (Admissible pair)**.** Given $g_1, g_2 \in I$, not both in I', let $Spol(g_1, g_2) = u_1 g_1 - u_2 g_2$ be the S-polynomial of g_1 and g_2. We have $u_i = \frac{lcm(LM(g_1), LM(g_2))}{LT(g_i)}$. We say that (g_1, g_2) is an **admissible pair** if:

(1) $LM(u_i)S(g_i) = x_i^{\alpha} e_{j_i} \notin LM(TSyz)$.
(2) $u_1 S(g_1) \neq u_2 S(g_2)$.

We remark that handling admissible pairs instead of normal pairs is harmless, as the latter is a subset of the former, and whether a pair is admissible can be checked easily before proceding to the corresponding reduction.

During the execution of the algorithm, when a polynomial $x^{\alpha} g$ is processed, it is at first not possible to know what is its signature. Algorithm 3 has computed $S_d(g)$ beforehand. Thanks to the F5 elimination criterion (Prop 3.7), we can detect some of the $x^{\alpha} g$ such that $S(x^{\alpha} g) \neq x^{\alpha} S(g)$ and eliminate them. For the processed polynomials, we use $x^{\alpha} S_d(g)$ as a **guessed signature** in the algorithm. Once an $\mathfrak{S}$-GB up to signature $< x^{\alpha} S_d(g)$ is computed, we have the following alternative. First case: $S_d(x^{\alpha} g) < x^{\alpha} S_d(g)$ and $x^{\alpha} g$ reduces to zero (by the computed $\mathfrak{S}_d$-GB up to signature $< x^{\alpha} S_d(g)$). The guessed signature was wrong but it is harmless as the polynomial is useless anyway. Second case: $S_d(x^{\alpha} g) = x^{\alpha} S_d(g)$, and then the guessed signature is certified. Once the criterion of Proposition 4.6 is satisfied, all (minimal) signatures are certified.

What happens when we can obtain f with signature $S_d(f) = x^{\alpha} e_i$ in degree d, and $S_{d+1}(f) = x^{\beta} e_j <_{sign} x^{\alpha} e_i$ in degree $d + 1$? Thanks to the way Algorithm 1 handles polynomials with always looking for smallest signature available, f and its multiples will then be built using only the second way. The first way will at most appear to be reduced by the first one.

5.2 Symbolic Preprocessing and Rewritten criterion

One of the main parts of the F5 algorithm 3 is the Symbolic Preprocessing : Algorithm 1. From the current set of S-pairs, sugar-degree d, and the current $\mathfrak{S}$-GB (up to sugar-degree $< d$), it produces a Macaulay matrix. One can read on the tropical reduction of this matrix new polynomials to append to the current basis to obtain an $\mathfrak{S}$-GB up to sugar-degree $\leq d$. It mostly consists of detecting which pairs are admissibles and selecting a (complete) set of reductors.

A special part of the algorithm is the usage of Rewritten techniques (due to Faugère (see [F02])).

The idea is the following. Once a polynomial has passed the F5 elimination criterion and is set to appear in a Macaulay matrix, it can be replaced by any other multiple of an element of G of the same signature. Indeed, assuming correctness of the algorithm without any rewriting technique, if one of them, h, is of signature $x^{\alpha} e_i$, the algorithm computes a tropical $\mathfrak{S}$-Gröbner basis up to signature $<_{sign} x^{\alpha} e_i$. Hence, h can be replaced by any other polynomial of same signature: it would be reduced to the same polynomial. By induction, one can prove all of them can be replaced at the same time. We also remark that this is still valid for replacing a row of a given guessed signature by another of the same guessed signature.

One efficient way is to replace a polynomial $t \times g$ by the the polynomial $x^{\beta} h$ ($h \in G$) of same (guessed) signature $tS(g)$ such that x^{β} has smallest degree.[3] Taking the sparsest available is another possibility. It actually leads to a substantial reduction of the running time of the F5 algorithm.

5.3 Linear algebra

To reduce the Macaulay matrices while respecting the signatures, we use the following tropical LUP algorithm from [V15]. If the rows correspond to polynomials ordered by increasing signature, it computes a row-reduction, respecting the signatures with each non-zero row with a different leading monomial.

5.4 A Complete Algorithm

We now provide with Algorithm 3 a complete version of an F5 algorithm wich uses Buchberger-F5 criterion and all the techniques introduced in this section.

Theorem 5.2. *Algorithm 3 computes an $\mathfrak{S}$-GB of I. It avoids tame trivial syzigies.*

Proof. It relies on Proposition 4.6. The proof is by induction on the sugar-degree, then i, then the $x^{\alpha} e_i$. One first proves that at the end of the main while loop any guessed signature is correct, or its row has reduced to zero, and then that $\mathfrak{S}_d$-GB are computed, signature by signature. Termination is a consequence of correctness and 3.13. For the syzygies, it is a consequence of Prop 3.7 and the fact that trivial syzygies of LM $x^{\alpha} e_i$ are such that $x^{\alpha} \in LM(I_{<_{sign} e_i})$. □

6 OTHER ALGORITHMS

6.1 Iterative F5

In this subsection, we present briefly another way of extending the F5 algorithm to the affine setting: a completely iterative way in the

[3]Indeed, such a h can be considered as one of the most reduced possible.

Algorithm 1: Symbolic-Preprocessing-Rewritten

input : P, a set of admissible pairs of sugar-degree d and G, a $\mathfrak{S}$-GB up to sugar-degree $d-1$

output: A Macaulay matrix of degree d

for *Q polynomial in P* **do**
  Replace Q in P by the polynomial $(uS(g), u \times g)$ with g latest added to G reaching the same guessed signature ;
$C \leftarrow$ the set of the **monomials** of the polynomials in P ;
$U \leftarrow$ the polynomials of P with their signature, except only one polynomial is taken by guessed signature ;
$D \leftarrow \emptyset$;
while $C \neq D$ **do**
  $m \leftarrow \max(C \setminus D)$;
  $D \leftarrow D \cup \{m\}$;
  $V \leftarrow \emptyset$;
  for $g \in G$ **do**
    if $LM(g) \mid m$ **then**
      $V \leftarrow V \cup \{(g, \frac{m}{LM(g)})\}$;
  $(g, \delta) \leftarrow$ the element of V with $\delta \times g$ of smallest guessed signature not already in the signatures of U, with tie-breaking by taking minimal δ (for degree then for $\leq_{sign}$) ;
  $U \leftarrow U \cup \{\delta \times g\}$;
  $C \leftarrow C \cup \{$monomials of $\delta \times g\}$;
$M \leftarrow$ the polynomials of U, written in a Macaulay matrix and ordered by increasing guessed signature ;
Return M ;

Algorithm 2: The tropical LUP algorithm

input : M, a Macaulay matrix of degree d in A, with n_{row} rows and n_{col} columns, and *mon* a list of monomials indexing the columns of M.

output: $\widetilde{M}$, the U of the tropical LUP-form of M

$\widetilde{M} \leftarrow M$;
if *$n_{col} = 1$ or $n_{row} = 0$ or M has no non-zero entry* **then**
  Return $\widetilde{M}$;
else
  for $i = 1$ *to* n_{row} **do**
    Find j such that $\widetilde{M}_{i,j}$ has the greatest term $\widetilde{M}_{i,j} x^{mon_j}$ for $\leq$ of the row i;
    Swap the columns 1 and j of $\widetilde{M}$, and the 1 and j entries of *mon*;
    By **pivoting** with the first row, eliminates the coefficients of the other rows on the first column;
    Proceed recursively on the submatrix $\widetilde{M}_{i \geq 2, j \geq 2}$;
  Return $\widetilde{M}$;

Algorithm 3: A complete F5 algorithm

input : $f_1, \ldots, f_s$ polynomials, ordered by degree

output: A tropical $\mathfrak{S}$-GB G of $\langle f_1, \ldots, f_s \rangle$

$G \leftarrow \{(e_i, f_i)$ for i in $[\![1, s]\!]\}$;
$B \leftarrow \{$guessed admissible pairs of $G\}$; $d \leftarrow 1$;
while $B \neq \emptyset$ **do**
  if *there is i s.t. $|f_i| = d$* **then**
    Replace the occurence of f_i in G by its reduction modulo $G \cap \langle f_1, \ldots, f_{i-1} \rangle$.
  P **receives** the pop of the admissible pairs in B of sugar-degree d. Update B accordingly;
  Write them in a Macaulay matrix M_d, along with their $\mathfrak{S}$-reductors obtained from G (one per signature) by **Symbolic-Preprocessing-Rewritten**(P, G) (Algorithm 1);
  Apply Algorithm 2 to compute the U in the tropical LUP form of M (no choice of pivot) ;
  Add to G all the polynomials obtained from $\widetilde{M}$ that provide new leading monomial up to their signature ;
  Add to B the corresponding new admissible pairs ;
  $d \leftarrow d + 1$;
Return G ;

initial polynomials. The idea is to compute tropical Gröbner bases for $\langle f_1 \rangle, \langle f_1, f_2 \rangle, \ldots, \langle f_1, \ldots, f_s \rangle$.

This corresponds to using the position over term ordering on the signatures, or in terms of filtration, to the following filtration on A^s:

Definition 6.1. We write that $x^\alpha e_i \leq_{incr} x^\beta e_j$ if:

(1) if $i < j$.
(2) if $i = j$ and $|x^\alpha f_i| < |x^\beta f_j|$.
(3) if $i = j$ and $|x^\alpha f_i| = |x^\beta f_j|$, and
- $x^\alpha \notin LM(I_{i-1})$ and $x^\beta \in LM(I_{i-1})$, or
- both $x^\alpha, x^\beta \in LM(I_{i-1})$ and $x^\alpha \leq x^\beta$, or
- both $x^\alpha, x^\beta \notin LM(I_{i-1})$ and $x^\alpha \leq x^\beta$.

Proposition 6.2 ([F02]). *If $x^\alpha \in LM(I_{i-1})$, then the filtration is constant at*

$$I_{\leq x^\alpha e_i}.$$

Proof. We can write $x^\alpha + g = \sum_{j<i} a_j f_j$, with for all j $a_j \in I$, and $g \in I$ with no monomial in $LM(I_{i-1})$. Then: $x^\alpha f_i = (-g) f_i + \sum_{j=1}^{i-1} (a_j f_i) f_j$, and the filtration is constant at $I_{\leq x^\alpha e_i}$. □

It is then possible to enounce a Buchberger-F5 criterion and provide an adapted F5 algorithm.

The two algorithms will then differ in the following way. **1.** For a given x^α and e_i, the vector space $I_{<x^\alpha e_i}$ is much bigger in the iterative setting, often of infinite dimension. Thus, polynomials of signature $x^\alpha e_i$ can be more deeply reduced. **2.** More syzygies can be avoided in the iterative setting. **3.** However, many more matrices are to be produced: one for each i and each necessary degree. Construction of the matrices is not mutualised by degree anymore.

6.2 F4

Another way to compute tropical Gröbner bases for affine polynomials is to adapt Faugère's F4 algorithm [F99]

Roughly, the F4 algorithm is an adaptation of Buchberger's algorithm such that: all S-polynomials of a given degree are processed and reduced together in a big Macaulay matrix, along with their reducers. The algorithm carries on the computation until there is no S-polynomials to reduce.

In a tropical setting, we have adapted the so-called "normal strategy" of F4 using the tropical LUP algorithm to reduce the Macaulay matrices. We have used Algorithm 2 to reduce the Macaulay matrices. So-called tropical row-echelon forms (Algorithm 3.2.2 and 3.7.3 of [V15]) are also possible, enabling to a trade-off between speed, thoroughness of the reduction and loss in precision.

7 NUMERICAL EXPERIMENTS

A toy implementation of our algorithms in Sagemath [Sage] is available on https://gist.github.com/TristanVaccon. We have gathered some numerical results in the following arrays. Timings are in seconds of CPU time.[4]

7.1 Benchmarks

Here, the base field is $\mathbb{Q}$ with 2-adic valuation. We have applied the tropical F5 algorithm, Algorithm 3, an iterative tropical F5, and a tropical F4 algorithm on the Katsura n and Cyclic n for varying n.

w=[0,...,0]	Katsura 4	5	6	7	Cyclic 4	5	6
Trop F5	.16	1.2	1371	•	0.4	21	•
Iterative trop F5	0.3	1.9	1172	•	0.4	21	•
Trop F4	.5	5	30	•	1.7	112	•

$w = [(-2)^{i-1}]$	Katsura 4	5	6	7	Cyclic 4	5	6
Trop F5	0.15	0.8	17	•	0.18	11	•
Iterative trop F5	0.18	1.1	20	•	0.18	11	•
Trop F4	0.2	1.7	15	•	1	65	•

7.2 Trop. F5+FGLM

For a given p, we take three polynomials with random coefficients in $\mathbb{Z}_p$ (using the Haar measure) in $\mathbb{Q}_p[x, y, z]$ of degree $2 \le d_1 \le d_2 \le d_3 \le 4$. We first compute a tropical Gröbner basis for a given weight w and the grevlex monomial ordering, and then apply an FGLM algorithm (tropical to classical as in Chapter 9 of [V15]) to obtain a lex GB. For any given choice of d_i's, we repeat the experiment 50 times. Coefficients of the initial polynomials are all given at some high-enough precision $O(p^N)$ for no precision issue to appear. We can not provide a certificate on the monomials of the output basis though. Results are compiled in the following arrays.

Firstly, an array for timings given as couples: average of the timings for the tropical F5 part and for the FGLM part, with $D = d_1 + d_2 + d_3 - 2$ the Macaulay bound. We add that for $p = 2, 3$, there is often a huge standard deviation on the timings of the F5 part.

$w =$ [0, 0, 0]	$D = 4$		5		6		7		8		9	
$p = 2$	.7	0.2	2.5	0.5	18	2.3	300	11	50	37	145	138
3	.8	.2	.9	.5	4	2	9	11	16	37	80	144
101	0.3	.2	.5	.5	1	2	3	10	4.6	37	11	150
65519	.4	.2	.6	.6	1.3	2.6	3.5	11	5	39	10	132

[4] Everything was performed on a Ubuntu 16.04 with 2 processors of 2.6GHz and 16 GB of RAM.

Coefficients of the output tropical GB or classical GB are known at individual precision $O(p^{N-m})$. We compute the total mean and max on those m's on the obtained GB. Results are compiled in the following array as couples of mean and max. The first array is for the F5 part and the second for the precision on the final result.

$w =$ [0, 0, 0]	$D = 4$		5		6		7		8		9	
$p = 2$	1.3	13	1.3	13	1.3	14	1.5	13	1.4	17	1.3	15
3	.6	6	.7	8	.7	7	.6	7	.6	7	.6	10
101	0	1	0	1	0	1	0	2	0	2	0	1
65519	0	0	0	0	0	1	0	0	0	0	0	0

$w =$ [0, 0, 0]	$D = 4$		5		6		7		8		9	
$p = 2$	8	71	17	170	58	393	167	913	290	1600	570	3900
3	5	38	13	114	27	230	81	640	167	1600	430	3100
101	.2	11	0	2	1.3	80	4	210	8	407	0	2
65519	0	0	0	0	0	0	0	0	0	0	0	0

Most of the loss in precision appears in the FGLM part. In comparison, the F5 part is quite stable, and hence, our goal is achieved.

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