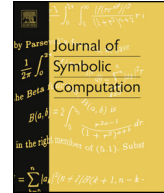




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On affine tropical F5 algorithms

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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 also provide a competitor with an adaptation of the F4 strategy to tropical Gröbner bases computations.

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.

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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 Maclagan and Sturmfels, 2015; Einsiedler et al., 2006) and even attempts at proving the Riemann hypothesis (see Connes, 2015).

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Effective computation over tropical varieties makes decisive use of Gröbner bases. Since Chan and Maclagan's definition of tropical Gröbner bases taking into account the valuation in Chan (2013), Chan and Maclagan (2019), computations of tropical Gröbner bases are available over fields with trivial or non-trivial valuation, but only in the 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 (Faugère, 2002), and has since then been widely studied and generalized (Bardet et al., 2014; Eder and Faugère, 2017).

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 Eder, 2013).

An F5 algorithm computing tropical Gröbner bases without any trivial reduction to 0, inspired by the classical F5 algorithm, has been described in Vaccon and Yokoyama (2017). 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 in Vaccon (2014, 2017) 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, 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 Vaccon, 2015), making it possible to compute a lexicographical (classical) Gröbner basis from a tropical one, paving the way to a complete strategy to solve polynomial systems of dimension zero over \mathbb{Q}_p , applying first an F5 algorithm and then an adaptation of the FGLM algorithm to go from a tropical Gröbner basis to a classical Gröbner basis.

We provide numerical data to estimate 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.

Another classical strategy to compute Gröbner bases is Faugère's F4 algorithm (Faugère, 1999). We provide a competitor to the F5 strategy with a tropical adaptation of F4, along with numerical data to compare their respective merits.

Up to our knowledge, this is the first study of an F4 algorithm in a tropical context. Regarding to computation at finite precision, there is a strong motivation for developing F4 algorithms along with F5 algorithms. In F4 algorithms, there is considerably more freedom in the choice of pivots during reduction. With more choices of reducers, a trade-off between speed and loss of precision is possible.

1.1. Related works

A canonical reference for an introduction to computational tropical algebraic geometry is the book of Maclagan and Sturmfels (2015).

The computation of tropical varieties over \mathbb{Q} with trivial valuation is available in the Gfan package by Anders Jensen (2017), by using standard Gröbner bases computations. Chan and Maclagan (2019) have developed a Buchberger algorithm to compute tropical Gröbner bases for homogeneous input polynomials (using a special division algorithm). Following their work, still for homogeneous polynomials, a Matrix-F5 algorithm has been proposed in Vaccon (2017) and a Tropical F5 algorithm in Vaccon and Yokoyama (2017). Markwig and Ren have provided a completely different technique of

computation using projection of standard bases in Markwig and Ren (2016), again only for homogeneous input polynomials.

In the classical Gröbner basis setting, many techniques have been studied to make the computation of Gröbner bases more efficient. In particular, Buchberger's algorithm is frequently made more efficient by using the *sugar-degree* (see Giovini et al., 1991; Bigatti et al., 2011) 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 Eder (2013).

A shorter version of this article has been published in the Proceedings of the 43rd International Symposium on Symbolic and Algebraic Computation (ISSAC 2018) with Vaccon et al. (2018). The main additions are the exposition of the results and proofs in Section 3 and 4, which have been improved and extended, and a new section with Section 7, introducing an F4 algorithm to compute tropical GB.

1.2. Specificities of computing 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 it 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 $G = (f_1, f_2) = (x + y, 2x + y)$ is a tropical GB over $\mathbb{Q}[x, y]$ with 2-adic valuation, $w = [0, 0]$ and grevlex ordering: the leading term of the first polynomial being x and that of the second being y . Nevertheless, the corresponding 2×2 matrix in the vector space of homogeneous polynomials of degree 1 is not under tropical row-echelon form.

As a consequence, reduction of a polynomial by a tropical GB is not easy. For example, if we try to apply the classical algorithm of division to reduce x by G , the sequence of remainders would be $-y, 2x, -2y, 4x, -4y, 8x, \dots$ and, while this sequence converges to zero, the division algorithm does not terminate.

In Chan (2013), Chan and MacLagan (2019), Chan and MacLagan relied on a variant of Mora's tangent cone algorithm to obtain an effective division algorithm. In Vaccon (2017), Vaccon and Yokoyama (2017), 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, and 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 paper (Eder, 2013) 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 homogeneous 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 ideals with more generators have a Gröbner basis with lower degree (Bardet et al., 2004), 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 (Vaccon and Yokoyama, 2017) works in an affine setting, and we characterize 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 Vaccon and Yokoyama (2017), 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 an ideal I generated by 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 (Definition 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 provides a Buchberger-F5 criterion on which Section 5 elaborates a first tropical F5 algorithm. Section 6 briefly presents another variant of the F5 algorithm to compute nonhomogeneous tropical Gröbner bases, and Section 7 introduces a tropical adaptation of the F4 algorithm. Finally, Section 8 displays numerical results related to the precision behavior and time-complexity of all 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 $f \in A$. In A^s , $(e_i)_{i=1}^s$ is the canonical basis.

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

Given a mapping $\phi: U \rightarrow V$, $Im(\phi)$ denotes 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 , i.e., $Im(M) = span(Rows(M))$. 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 basis (*tropical GB* for short):

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

2.3. Relation to definitions in other works

We can remark that for homogeneous polynomials our definitions coincide with those given in Vaccon and Yokoyama (2017).

Still for homogeneous polynomials, our definition of $LM(f)$ coincides with that of $lm(f)$ in the article by Chan and Maclagan (2019), similarly our $LC(f)$ and their $lc(f)$ coincides, and our $LT(f)$ equals to the product $lc(f) \times lm(f)$, and hence, we compute the same tropical Gröbner bases. None of them should be mistaken with their $\text{in}_w(f)$ which lives in a residue ring and not in the polynomial ring A .

Remark 2.11 of Chan and Maclagan (2019) warns against a direct generalization of their definition to the affine setting, with the fact that $f = (x + 2x^2) \in \langle x \rangle$, $LM(f)$ generates $LM(\langle x \rangle)$ but f do not generate $\langle x \rangle$.

One reason why such a problem do not occur in our setting is the fact that we take first the degree into account.

While this choice is meaningful for our goal of solving polynomial systems over \mathbb{Q}_p , it is not enough by itself if, in a tropical setting, one wants to recover the initial terms of an ideal defined without taking into account the degree of the monomials.

If one is interested in Gröbner bases computation where one takes into account the valuation of the coefficients and not the degree of the monomials, we refer to the theory of Gröbner bases over Tate algebras in Caruso et al. (2019).

3. Filtration and \mathfrak{S} -GB

3.1. Definition and elimination criterion

One of the main ingredients 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 . For simplicity, we assume that they are ordered by increasing degree.

First, we define an order on the monomials of the vector space A^s . To that intent, we highlight some monomials which appear as leading monomial of a syzygy.

Definition 3.1. Let $(a_1, \dots, a_s) \in A^s$ and $i \in \{1, \dots, s\}$ 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 $LM(TSyz(F))$ as the module in A^s generated by the leading monomials of the tame syzygies.

Trivial tame syzygies are the tame syzygies that are also trivial, i.e., in the module generated by the $f_i e_j - f_j e_i$.

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 .

For our definition, we need a monomial ordering \leq_m on A . Any such order \leq_m is possible, and \leq_m need not be related to \leq_1 and \leq .

We can then define a total order on the monomials of A^s .

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

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

Remark 3.3. To clarify, we have defined so far 4 different orders:

- the order $<_1$ is an order on the *monomials* of A ;
- the order $<$ is an order on the *terms* of A , which is compatible with the tropical structure, and uses $<_1$ to break ties;
- the order $<_m$ is an order on the *monomials* of A ;
- the order $<_{\text{sign}}$ is an order on the *monomials* of A^s , which uses $<_m$ to break ties.

The orders $<_1$ and $<_m$ need not be related, because they are only used for breaking ties when comparing objects which are not related: tropical terms in A and monomials in A^s .

In practice, the order $<_m$ is only used to break ties at points where the actual order does not matter. As such, it can be any monomial order.

Remark 3.4. The order $<_{\text{sign}}$ defined here may not satisfy Convention 2.1 (a) in Eder and Faugère (2017): it may happen that $x^\alpha <_1 x^\beta$ or $x^\alpha < x^\beta$, and yet that $x^\alpha e_i >_{\text{sign}} x^\beta e_i$. Namely, it will happen if $x^\beta e_i \notin LM(TSyz(F))$ and $x^\alpha e_i \in LM(TSyz(F))$, or if both lie in or out of $LM(TSyz(F))$ and $x^\beta <_m x^\alpha$.

This convention, in a tropical setting, leads to further problems, since terms are ordered differently than monomials.

However, the reason for that assumption in Eder and Faugère (2017), as well as in most signature-based works in a classical setting, is to ensure that one can read the leading term of syzygies from their signature, for the F5 elimination criterion. In our scenario, the last clause of Definition 3.2 serves this purpose, and allows us to prove the F5 elimination criterion in a tropical setting (Proposition 3.13).

Definition 3.5. We consider the vector space

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

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

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

Definition 3.6. For $f \in I$, the smallest $x^\alpha e_i$ such that $f \in I_{\leq \text{sign } x^\alpha e_i}$ is called the *signature* of f and noted $S(f)$.

Example 3.7. Let $F = (x^2y + 1, x^3 + 1, y^3 - x, y^3 - y) \in \mathbb{Q}_2[x, y]$ with $w = (0, 0)$. Let \leq_m and \leq_1 be the graded lexicographical ordering. Then $S(x - y) = ye_2$, as $x - y = x \times (x^2y + 1) - y \times (x^3 + 1)$, even though $x - y = -1 \times (y^3 - x) + 1 \times (y^3 - y)$.

We shall also need the notion of sugar-degree, as introduced and explored in Giovini et al. (1991), Bigatti et al. (2011).

Definition 3.8. We define $|x^\alpha e_i| := |x^\alpha f_i|$ to be the *sugar-degree* of $x^\alpha e_i$.

For the purpose of Algorithm 3, we design a filtration compatible with the sugar-degree.

Definition 3.9. We consider the vector space

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

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

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

Definition 3.10. For $d \in \mathbb{Z}_{>0}$ and $f \in I^{\leq d}$, the smallest $x^\alpha e_i$ such that $f \in I_{\leq \text{sign } x^\alpha e_i}^{\leq d}$ is called the *d-signature* of f and noted $S_d(f)$.

Remark 3.11. $S_d(f)$ can be different from $S(f)$ for small d , but given an f , all $S_d(f)$ are equal when d is large. Moreover, for any $f \in I^{\leq d}$, $S(f) \leq \text{sign } S_d(f)$.

Example 3.12. We set $F = (x^2y + 1, x^3 + 1, y^3 - x, y^3 - y) \in \mathbb{Q}_2[x, y]$ as in Example 3.7. Then $S_3(x - y) = e_4$ as $x - y = -1 \times (y^3 - x) + 1 \times (y^3 - y)$, whereas $S_4(x - y) = ye_2 = S(x - y)$ since $x - y = x \times (x^2y + 1) - y \times (x^3 + 1)$.

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

The goal of the F5 criterion is to recognize some $x^\alpha e_i$ such that the filtration is constant at $I_{\leq \text{sign } x^\alpha e_i}^{\leq d}$. 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 3.13 (Faugère (2002)). If x^α is such that $x^\alpha e_i \in \text{LM}(\text{TSyz}(F))$, $d \geq |x^\alpha f_i|$, then the filtration is constant at $I_{\leq \text{sign } x^\alpha e_i}^{\leq d}$. Such an $x^\alpha e_i$ can be characterized using the following statement. If $x^\alpha \in \text{LM}(I_{\leq \text{sign } x^\beta e_j}^{\leq d})$ for some x^β and j such that $|x^\beta f_j| \leq |x^\alpha|$, then $x^\alpha e_i \in \text{LM}(\text{TSyz}(F))$ for any $i > j$. A partial converse is possible: if $x^\alpha e_i \in \text{LM}(\text{TSyz}(F))$ is the leading monomial of a trivial tame syzygy, then there exists some x^β and j such that $|x^\beta f_j| \leq |x^\alpha|$ and $x^\alpha \in \text{LM}(I_{\leq \text{sign } x^\beta e_j}^{\leq d})$.

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:

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

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

For the characterization, we can first write $x^\alpha + g = \sum_{k \leq j} a_k f_k$, with $LT(g) < x^\alpha$ and for all $k \leq j$, $|a_k f_k| \leq |x^\beta f_j| \leq |x^\alpha|$. 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 $k \leq j$. The partial converse statement is clear using the fact that trivial syzygies of leading monomial $x^\alpha e_i$ are such that $x^\alpha \in LM(\langle f_1, \dots, f_{i-1} \rangle)$. \square

In concrete terms, during the computation of a Gröbner basis, we can omit any appearance of any $x^\alpha f_i$ such that $x^\alpha e_i \in LM(TSyz(F))$ and $d \geq |x^\alpha f_i|$. We can recognize such a polynomial using the second part of the proposition. This will be used to eliminate unnecessary S-polynomials. For example, using the notations of 3.12, $I_{<_{\text{sign}} x^2 y e_2}^{\leq 6} = I_{\leq_{\text{sign}} x^2 y e_2}^{\leq 6}$, and we can avoid any appearance of $x^2 y f_2$ in our computations.

If all the f_i 's are homogeneous, this criterion coincides with the usual F5 elimination criterion, as for example stated in Vaccon and Yokoyama (2017), 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 which are compatible with the filtration: tropical \mathfrak{S} -GB. We first need the definition of reductions compatible with the filtration and the corresponding irreducible polynomials.

Definition 3.14 (Regular \mathfrak{S} -reduction). Let $e, g \in I$, $h \in I$. We say that e regular \mathfrak{S} -reduces to g with h , $e \xrightarrow{h}_{\mathfrak{S}} g$, if there are $t \in T$ and $\alpha \in k^*$ such that:

- $e - \alpha th = g$, and either $g = 0$ or $LT(g) < LT(e)$, $LM(g) \neq LM(e)$.
- $S(th) <_{\text{sign}} S(e)$.

We should remark that in the previous definition, we ask for the condition $LM(g) \neq LM(e)$ so as to ensure that the leading monomial of e is eliminated. For example, reducing x^2 by $x + y$ into $2x^2 + xy$ would never be acceptable.

We can naturally define then what is an regular \mathfrak{S} -irreducible polynomial.

Definition 3.15 (Regular \mathfrak{S} -irreducible polynomial). We say that $g \in I$ is regular \mathfrak{S} -irreducible if there is no $h \in I$ which regular \mathfrak{S} -reduces g . If there is no ambiguity, we might simply call g irreducible.

Example 3.16. We use $F = (x^2 y + 1, x^3 + 1, y^3 - x, y^3 - y) \in \mathbb{Q}_2[x, y]$ as in Example 3.7. Then $x^3 y + y = y \times (x^3 + 1)$ regular \mathfrak{S} -reduces to $-x + y$, which is irreducible, and its signature is ye_2 .

Definition 3.17 (Tropical \mathfrak{S} -Gröbner basis). We say that $G \subset I$, a set of regular \mathfrak{S} -irreducible 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 , if for each regular \mathfrak{S} -irreducible polynomial $h \in I$, there exist $g \in G$ and $t \in T$ such that $LM(th) = LM(h)$ and $tS(g) = S(h)$.

Definition 3.18. Definitions 3.14, 3.15 and 3.17 have natural analogues when one restricts to the vector space $I^{\leq d}$ and S_d with regular \mathfrak{S}_d -reduction, regular \mathfrak{S}_d -irreducible polynomial and tropical \mathfrak{S}_d -GB.

These definitions also extends naturally when one restricts to the vector spaces $I_{\leq_{\text{sign}} x^\alpha e_i}$ or $I_{\leq_d}^{\leq_{\text{sign}} x^\alpha e_i}$, providing respectively \mathfrak{S} -GB up to signature $x^\alpha e_i$ and \mathfrak{S}_d -GB up to d -signature $x^\alpha e_i$.

Example 3.19. We use $F = (x^2y + 1, x^3 + 1, y^3 - x, y^3 - y) \in \mathbb{Q}_2[x, y]$ as in Example 3.7. Then $G = (x^2y + 1, x^3 + 1, x - y, y^3 - 1, y - 1)$, with respective signatures $(e_1, e_2, ye_2, xy^2e_2, e_3, e_4)$, is a tropical \mathfrak{S} -GB of I .

Proposition 3.20. *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 $S(tg) = tS(g) <_{\text{sign}} S(h)$ otherwise.

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

Proof. For h irreducible, the result is simply a consequence of the definition of a tropical \mathfrak{S} -GB. When h is regular \mathfrak{S} -reducible, it means that it can be reduced by h_2 a polynomial with same leading term but such that $S(h_2) <_{\text{sign}} S(h)$. If h_2 is irreducible, we are done. Otherwise, there exists h_3 with same leading term and such that $S(h_3) <_{\text{sign}} S(h_2)$, and so on. A consequence of Definition 3.2 is that there is no strictly decreasing sequence of monomials for \leq_{sign} . Consequently, after a finite number of iterations, we find h' with same leading term as h , irreducible and such that $S(h') <_{\text{sign}} S(h)$. We can then apply the definition of a tropical \mathfrak{S} -GB to conclude. \square

Corollary 3.21. *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 3.13 to our advantage when computing these tropical \mathfrak{S} -GB. Moreover, we also have the following finiteness result:

Proposition 3.22. *Every tropical \mathfrak{S} -Gröbner basis contains a finite tropical \mathfrak{S} -Gröbner basis.*

Proof. It is a property of the structure of monomial ideals, and the proof in the classical case from Arri and Perry (2011, Prop. 14), using Dickson's lemma, can directly be transposed to the tropical setting. \square

3.3. Linear algebra and existence

For $x^\alpha \in T$ and $1 \leq i \leq n$, let us denote by $Mac_{\leq_{\text{sign}} x^\alpha e_i}(F)$ the Macaulay matrix of the polynomials $x^\beta f_j$ such that $x^\beta e_j \leq x^\alpha e_i$, 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 for more information¹) and obtain all the leading monomials in $I_{\leq_{\text{sign}} x^\alpha e_i}$. This can be (theoretically) performed for all $x^\alpha e_i$ to obtain the existence of an \mathfrak{S} -GB of I .

3.4. Singular reduction

If one allows large inequality in the signature condition of Definition 3.14, one gets the notion of \mathfrak{S} -reduction.

¹ We can summarize that the tropical LUP algorithm is an adaptation of a row-echelon form computation to the tropical setting so that one can read the leading monomials in the tropical sense from the rows of the reduced matrix.

Definition 3.23 (\mathfrak{S} -reduction). Let $e, g \in I$, $h \in I$. We say that e \mathfrak{S} -reduces to g with h , $e \rightarrow_{\mathfrak{S}}^h g$, if there are $t \in T$ and $\alpha \in k^*$ such that:

- $e - \alpha th = g$, and either $g = 0$ or $LT(g) < LT(e)$, $LM(g) \neq LM(e)$.
- $S(th) \leq_{\text{sign}} S(e)$.

A \mathfrak{S} -reduction which is not regular, i.e., with $S(th) = S(e)$, is called a *singular \mathfrak{S} -reduction*.

As a consequence, \mathfrak{S} -GB have the following generating property.

Proposition 3.24. *If G is an \mathfrak{S} -GB, then any $f \in I$ can be reduced to 0 using \mathfrak{S} -reductions by multiples of elements of G .*

3.5. More on signatures

We define Σ to be the set of signatures.

Thanks to Proposition 3.13, not all $x^\alpha e_i$ can be a signature:

Remark 3.25. If $x^\alpha e_i \in LM(TSyz(F))$ then $x^\alpha e_i \notin \Sigma$.

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

Lemma 3.26. *If $f, g \in I$ are such that $S(f) = S(g)$ and $LM(f) \neq LM(g)$, then there exist $b \in k^*$ such that $S(f + bg) < S(f)$ and $f + bg \neq 0$.*

If one takes the point of view of linear algebra, the proof is direct. This Lemma has a direct consequence on regular \mathfrak{S} -irreducible polynomials.

Lemma 3.27. *All regular \mathfrak{S} -irreducible polynomials of a given signature share the same leading monomial.*

We finally state one last lemma about the compatibility of signatures with multiplication.

Lemma 3.28. *If $g \in I$ and $\tau \in T$ then $S(\tau g) \leq_{\text{sign}} \tau S(g)$. 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 $r \in I_{<_{\text{sign}} \tau S(g)}$ 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 $S(\mu g) <_{\text{sign}} \mu S(g)$. Then $S(\tau g) = S(\frac{\tau}{\mu} \mu g) \leq_{\text{sign}} \frac{\tau}{\mu} S(\mu g) <_{\text{sign}} \frac{\tau}{\mu} \mu S(g) = \tau S(g)$, which is a contradiction. \square

Lemma 3.29. *The previous lemmata, 3.26, 3.27, 3.28 are also true if one uses \mathfrak{S}_d -signature instead of signatures when restricting to $I^{\leq d}$.*

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, before we can state the Buchberger-F5 criterion.

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

1. the g_i 's are regular \mathfrak{S} -irreducible polynomials.
2. $S(u_i g_i) = \text{LM}(u_i) S(g_i)$ for $i = 1, 2$.
3. $S(u_1 g_1) \neq S(u_2 g_2)$.

We define accordingly d -normal pairs in $I^{\leq d}$.

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

1. for all $i \in \llbracket 1, s \rrbracket$, 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 regular \mathfrak{S} -irreducible and $tS(g) = S(tg) = S(\text{Spol}(g_1, g_2))$.

Then G is a \mathfrak{S} -Gröbner basis of I . The analogue result using d -normal pairs to recognize an \mathfrak{S}_d -GB in $I^{\leq d}$ is also true.

Remark 4.3. The converse of this result is clear.

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 Chan, 2013). First we need two lemmata.

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

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

Proof. Exercise 8 in Section 2.6 of Cox et al. (2015). \square

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 $S(h) \leq_{\text{sign}} \sigma$. Then there exist $r \in \mathbb{N}$, $g_1, \dots, g_r \in G$, $Q_1, \dots, Q_r \in A$ such that for all i and x^α a monomial of Q_i , $S(x^\alpha g_i) = x^\alpha S(g_i) \leq_{\text{sign}} S(h)$ and $\text{LT}(Q_i g_i) \leq \text{LT}(h)$, 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 τg with $\tau \in T$, $g \in G$ such that $S(\tau g) = \tau S(g) \leq_{\text{sign}} S(h)$. Only one row is possible per non-zero signature, and each monomial in $\text{LM}(I^{\leq_{\text{sign}} \sigma})$ is reached as leading term by only one row. It is then enough to add a row corresponding to 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 . \square

Proof of Theorem 4.2. We prove the main result by induction on the signature. We follow the order \leq_{sign} for the induction. It is clear for $\sigma = e_1$. It is also clear that if we have an \mathfrak{S} -GB up to $<_{\text{sign}} e_i$ then we have an \mathfrak{S} -GB up to $\leq_{\text{sign}} e_i$. We write the elements of G as g_1, \dots, g_r for some $r \in \mathbb{Z}_{>0}$.

Let us assume that G is an \mathfrak{S} -GB up to signature $<_{\text{sign}} \sigma$ for some signature σ and let us prove it is a \mathfrak{S} -GB up to $\leq_{\text{sign}} \sigma$. We can assume that all $g \in G$ satisfy $\text{LC}(g) = 1$. Let $P \in I$ be irreducible, with $\text{LC}(P) = 1$ and such that $S(P) = \sigma$. We prove that there is $\tau \in T$, $g \in G$ such that $\text{LM}(P) = \text{LM}(\tau g)$ 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 $LM(\tau g) = LM(P)$ we are done. Otherwise, by Lemma 3.26, there exists some $b \in k^*$ such that $S(P + b\tau g) = \sigma'$ for some $\sigma' <_{\text{sign}} \sigma$.

We can apply Lemma 4.5 to $P + b\tau g$ and obtain that there exist $h_1, \dots, h_r \in A$, such that $P = \sum_{i=1}^r h_i g_i$, and for all i , and $x^{\gamma'}$ monomial of h_i , the $x^{\gamma'} S(g_i) = S(x^{\gamma'} g_i) \leq_{\text{sign}} \sigma$ 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 possible values of $\max_i (LT(g_i h_i))$'s. Such a β exists thanks to Lemma 2.10 in Chan and MacLagan (2019) (whose adaptation to the non-homogeneous setting is straightforward). 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 $S(\tau g_i) = \tau S(g_i) \leq_{\text{sign}} \sigma$.

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

We can renumber the g_i 's so that, for some d :

- $\beta \leq m_1 \leq \dots \leq m_d$.
- $\beta > m_i$ for $i > d$.

We can assume that among the set of possible (h_1, \dots, h_r) that reach β , we take one such that this d is minimal. Since $LT(P) < \beta$, we have $d \geq 2$.

We can write (using the fact that $LC(g_1) = LC(g_2) = 1$):

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

By construction, $LM(h_1)S(g_1) \neq LM(h_2)S(g_2)$. By Lemma 4.4, there exists a term μ such that $\mu \frac{\text{lcm}(LM(g_1), LM(g_2))}{LM(g_i)} = LM(h_i)$ for $i \in \{1, 2\}$. Using Lemma 3.28, we get that (g_1, g_2) is a normal pair.

If $S(\text{Spol}(g_1, g_2)) = \sigma$, by the second property of the F5 criterion, we are done. Indeed, it provides us with some t_0 and g_0 such that $t_0 g_0$ is regular \mathfrak{S} -irreducible with signature σ , and as all regular \mathfrak{S} -irreducible polynomials of a given signature share the same leading monomial, thanks to Lemma 3.27, we have with t_0 and g_0 a satisfying τ and g .

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

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

Then we have $S(L \cdot \text{Spol}(g_1, g_2)) \leq_{\text{sign}} \sigma$ thanks to Lemma 4.4. Using the same construction as before with the second assumption of the F5 criterion and Lemmata 3.26 and 4.5, we obtain some h'_i 's such that $L \cdot \text{Spol}(g_1, g_2) = \sum_{i=1}^r h'_i g_i$, $LT(h'_i g_i) \leq LT(L \cdot \text{Spol}(g_1, g_2)) < \beta$ for all i . Furthermore, the signatures $S(x^\alpha g_i) = x^\alpha S(g_i)$ for $i \in \{1, \dots, r\}$ and x^α in the support of h'_i are all distinct.

We then get:

$$\begin{aligned} P &= \sum_{i=1}^r h_i g_i, \\ &= \sum_{i=1}^r h_i g_i - L \cdot \text{Spol}(g_1, g_2) + \sum_{i=1}^r h'_i g_i, \\ &= \left(h_1 - LC(h_1 g_1) \frac{x^u}{LM(g_1)} + h'_1 \right) g_1 \\ &\quad + \left(h_2 + LC(h_1 g_1) \frac{x^u}{LM(g_2)} + h'_2 \right) g_2 + \sum_{i=3}^r (h_i + h'_i) g_i, \end{aligned}$$

$$=: \sum_{i=1}^r \tilde{h}_i g_i,$$

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

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

As a consequence, we have obtained a new expression for f with either $\max_i(LT(h_i g_i)) < \beta$ or this term attained strictly 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 of the main result. It is then direct to adapt the previous proof to the case of an \mathfrak{S}_d -GB. \square

This theorem holds also for \mathfrak{S} -GB (or \mathfrak{S}_d -GB) up to a given signature. We have the following variant 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 regular \mathfrak{S}_d -irreducible in $I^{\leq d}$.*
2. *For all $g_1, g_2 \in G$ we have $g_1, g_2 \in I^{\leq d}$ along with $Spol(g_1, g_2)$ and both sides of the S -pair for g_1 and g_2 .*
3. *For all $i \in \llbracket 1, s \rrbracket$, 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 d -normal pair, there exists $g \in G$ and $t \in T$ such that tg is regular \mathfrak{S}_d -irreducible and $tS_d(g) = S_d(tg) = S_d(Spol(g_1, g_2))$.*

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

Proof. Using Theorem 4.2, it is clear that such a G is an \mathfrak{S}_d -GB.

It remains to prove that G is then an \mathfrak{S} -GB.

A first remark is if σ is a signature then for any $f \in I^{\leq d}$, if $S_d(f) = \sigma$ then $S(f) = \sigma$. It is a consequence of Remark 3.11.

A second remark is that if $f \in I^{\leq d}$ is such that $S_d(f) \leq_{\text{sign}} \sigma$, then $S(f) \leq_{\text{sign}} \sigma$.

One can then use the same proof on induction on σ as for Theorem 4.2 except for the decomposition of $LSpol(g_1, g_2)$ in signature $\leq_{\text{sign}} \sigma$ in terms of the g_i 's. If $S(LSpol(g_1, g_2)) <_{\text{sign}} \sigma$, then it is true by induction. Otherwise, $S(LSpol(g_1, g_2)) = \sigma$, and as (g_1, g_2) is a d -normal pair, then $S_d(LSpol(g_1, g_2)) = \sigma$ by the first remark. One can then use the \mathfrak{S}_d -GB property, and the second remark. Given the decomposition, all arguments are the same. \square

Remark 4.7. When going from \mathfrak{S}_d to \mathfrak{S} , one should be aware that signatures can drop, even for regular \mathfrak{S}_d -irreducible polynomials. For instance, looking back to Example 3.12, $x - y$ is regular \mathfrak{S}_d -irreducible, with $S_d(x - y) = e_4$ when $d = 3$. Then, $x - y$ is also regular \mathfrak{S} -irreducible, but of signature ye_2 . If instead, we had taken a small variation with $F = [x^2y + 1, x^3 + 1, y^3 + x, y^3 + y]$, then e_4 is not even a signature. It is an \mathfrak{S}_3 -signature but disappears in sugar-degree 4 as $y^3 + y = -x \times (x^2y + 1) + y \times (x^3 + 1) + (y^3 + x)$, and the signature of $y^3 + y$ is e_3 .

Fortunately, Proposition 4.6 is enough to tell when d is big enough for an \mathfrak{S}_d -GB to be an \mathfrak{S} -GB (even though signatures might still drop going from \mathfrak{S}_d to \mathfrak{S}).

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 with which pairs to proceed and how to build the Macaulay matrices and reduce them.

The main algorithm is Algorithm 3 (on page 147), and will be presented in the last part of this section. Two key subfunctions are the Symbolic Preprocessing algorithm, used to build the Macaulay matrices processed by the main algorithm and given as Algorithm 1 (on page 146) and the Tropical LUP algorithm, used to reduce those matrices, and given as Algorithm 2 (on page 146).

We recommend that the reader first take a look at the main algorithm, Algorithm 3 on page 147, in order to get a global idea before reading linearly this Section.

5.1. Admissible pairs and guessed signatures

It is not possible to check the second condition in the Definition 4.1 in advance in an F5 algorithm. Indeed, one needs an \mathfrak{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 (*d-Admissible pair*). Given $g_1, g_2 \in I^{\leq d}$, let $\text{Spol}(g_1, g_2) = u_1 g_1 - u_2 g_2$ be the S -polynomial of g_1 and g_2 . We have

$$u_i = \frac{\text{lcm}(\text{LM}(g_1), \text{LM}(g_2))}{\text{LT}(g_i)}.$$

We say that (g_1, g_2) is a *d-admissible pair* if:

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

To certify that a set is an \mathfrak{S}_d -GB, handling d -admissible pairs instead of d -normal pairs is harmless. Indeed, d -normal pairs in $I^{\leq d}$ are contained inside the d -admissible pairs. Whether a pair is d -admissible can be checked easily before proceeding to reduction using the second part of the F5 elimination criterion (Proposition 3.13).

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 (on page 147) has computed $S_d(g)$ beforehand. Thanks to the F5 elimination criterion (Proposition 3.13), 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 $<_{\text{sign}} x^\alpha S_d(g)$ is computed, we have the following alternative. First case: $S_d(x^\alpha g) <_{\text{sign}} x^\alpha S_d(g)$ and $x^\alpha g$ reduces to zero (by the computed \mathfrak{S}_d -GB up to d -signature $<_{\text{sign}} x^\alpha S_d(g)$) using possibly singular reduction (as in Subsection 3.4). 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 signatures are certified.

What happens when we can obtain f with signature $S_d(f) = x^\alpha e_i$ in degree d , and $S_{d+1}(f) = x^\beta e_j <_{\text{sign}} x^\alpha e_i$ in degree $d+1$? Thanks to the way Algorithm 1 (on page 146) handles polynomials, always looking for smallest signature available, f and its multiples will then be built using only the second way. The first way of writing will at most appear so as to be reduced by the second one.

For instance, if we look back at Example 3.12, $(e_4, x - y)$ will only be used in sugar-degree 3. In sugar-degree 4 and more, it is $(ye_2, x - y)$ that will appear. $(e_4, x - y)$ may only appear in sugar-degree 4 to be reduced to 0 by $(ye_2, x - y)$.

5.2. Symbolic preprocessing and rewritten criterion

One of the main parts of the F5 algorithm, Algorithm 3 (on page 147), is the Symbolic Preprocessing: Algorithm 1 on page 146. From the current set of S -pairs, sugar-degree d , and the current \mathfrak{S}_{d-1} -GB, 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}_d -GB. It mostly consists of detecting which pairs are admissible and selecting a (complete) set of reducers.

A special part of the algorithm is the use of Rewritten techniques (due to Faugère, 2002).

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 d -signature. Indeed, assuming correctness of the algorithm without any rewriting technique, if one of them, h , is of d -signature $x^\alpha e_i$, the algorithm computes a tropical \mathfrak{S} -Gröbner basis up to d -signature $<_{\text{sign}} x^\alpha e_i$. 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 that 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 d -signature by another of the same guessed d -signature.

Algorithm 1: Symbolic-Preprocessing-Rewritten.

input : P , a set of $d - 1$ -admissible pairs of sugar-degree d and G such that $G \cap I^{\leq d-1}$ is an \mathfrak{S}_{d-1} -GB
output: A Macaulay matrix
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 \leq_m) ;
 $U \leftarrow U \cup \{\delta \times g\}$;
 $C \leftarrow C \cup \{\text{monomials of } \delta \times g\}$;
 $M \leftarrow$ 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: \tilde{M} , the U of the tropical LUP-form of M
 $\tilde{M} \leftarrow M$;
if $n_{col} = 1$ or $n_{row} = 0$ or M has no non-zero entry **then**
 Return \tilde{M} ;
else
 for $i = 1$ to n_{row} **do**
 Find j such that $\tilde{M}_{i,j}$ has the greatest term $\tilde{M}_{i,j}x^{mon_j}$ for \leq of the row i ;
 Swap the columns 1 and j of \tilde{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 $\tilde{M}_{i \geq 2, j \geq 2}$;
 Return \tilde{M} ;

One efficient way is to replace a polynomial $t \times g$ by the polynomial $x^\beta h$ ($h \in G$) of same (guessed) d -signature $tS_d(g)$ such that x^β has smallest degree.² It actually leads to a substantial reduction of the running time of the F5 algorithm. Taking the sparsest available polynomial is another possibility.

5.3. Linear algebra

To reduce the Macaulay matrices while respecting the signatures, we use the following tropical LUP algorithm from Vaccon (2017): Algorithm 2 on page 146. If the rows correspond to polynomials ordered by increasing signature, the algorithm computes a *row-reduction* of the matrix, respecting the signatures and the tropical ordering, and such that each resulting non-zero row has a different leading monomial. As a consequence, we get on the resulting matrix all the leading monomials in the vector space generated by the rows of the initial matrix.

Example 5.2. We provide here a small example to illustrate the tropical LUP algorithm.

² Indeed, such an h can be considered as one of the most reduced possible.

Algorithm 3: A complete F5 algorithm.

input : f_1, \dots, f_s polynomials, ordered by degree
output: A tropical \mathfrak{S} -GB G of $\langle f_1, \dots, f_s \rangle$
 $G \leftarrow \{(e_i, f_i) \text{ for } i \text{ in } \llbracket 1, s \rrbracket\}$;
 $B \leftarrow \{\text{S-pairs of } G\}$; $d \leftarrow 1$;
while $B \neq \emptyset$ **do**
 if there is i s.t. $|f_i| = d$ **then**
 Replace the occurrence of f_i in G by its reduction modulo $G \cap \langle f_1, \dots, f_{i-1} \rangle$;
 P receives the pop of the $d - 1$ -admissible pairs in B of sugar-degree d . Suppress from B the others of sugar-degree d ;
 Write them in a Macaulay matrix M_d , along with their regular \mathfrak{S}_d -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 \tilde{M} that provide new leading monomial up to their d -signature ;
 Add to B the corresponding new d -admissible pairs ;
 $d \leftarrow d + 1$;
Return G ;

We start with the following Macaulay matrix, over $\mathbb{Q}_3[x, y]$ with $w = (0, 0)$, and \leq_m and \leq_1 are the graded lexicographical ordering.

$$\begin{array}{c|ccccc}
 & x^4 & x^3y & y^4 & x^2 & xy & y^2 \\
 ye_3 & 1 & & & & & 3 \\
 x^2e_3 & & & & 1 & 9 & 3 \\
 ye_4 & 3 & 9 & 9 & & & \\
 e_5 & & 9 & 9 & 3 & 1 & 9
 \end{array}$$

The $x^\alpha e_i$'s are the signatures of the polynomials corresponding to the rows that are given as entry of the algorithm. In this case, mon is $[x^4, x^3y, y^4, x^2, xy, y^2]$.

The output of the tropical LUP algorithm is then the following matrix.

$$\begin{array}{c|ccccc}
 & x^4 & x^2 & x^3y & xy & y^4 & y^2 \\
 ye_3 & 1 & & & & & 3 \\
 x^2e_3 & & 1 & & 9 & & 3 \\
 ye_4 & & & 9 & 9 & 9 & \\
 e_5 & & & & -35 & 0 & -18
 \end{array}$$

5.4. A complete algorithm

We now provide with Algorithm 3 on page 147 a complete version of an F5 algorithm which uses Buchberger-F5 criterion and all the techniques introduced in this section.

Theorem 5.3. Algorithm 3 (on page 147) computes an \mathfrak{S} -GB of I . It avoids trivial tame syzygies.

Proof. It relies on Theorem 4.2 and then 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. One can then apply 4.6 on the output to conclude. Termination is a consequence of correctness and Proposition 3.22. For the syzygies, it is a direct consequence of the second part of Proposition 3.13. \square

Remark 5.4. Condition 1 of 4.2 and 3 of 4.6 is not satisfied when for some i , $f_i \in \langle f_1, \dots, f_{i-1} \rangle$. This is harmless as: 1. As soon as it is found by computation, no signature in e_i will appear anymore. 2. The Buchberger-F5 criterion can be applied omitting f_i .

6. Iterative F5

In this section, we present briefly another way of extending the F5 algorithm to the affine setting: a completely iterative way in the initial polynomials. The idea is to compute tropical Gröbner bases for $\langle f_1 \rangle, \langle f_1, f_2 \rangle, \dots, \langle f_1, \dots, f_s \rangle$.

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 $x^\alpha e_i \leq_{\text{incr}} x^\beta e_j$ 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 (Faugère (2002)). 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 $I_{\leq x^\alpha e_i}$. \square

It is then possible to state 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 $I_{<_{\text{incr}} x^\alpha e_i}$ 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.

7. The F4 approach

Another way to compute tropical Gröbner bases for affine polynomials is to adapt Faugère's F4 algorithm (Faugère, 1999).

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.

For simplicity of exposition, we have only used Algorithm 2 to reduce the Macaulay matrices.

Nevertheless, so-called tropical row-echelon forms (Algorithm 3.2.2 and 3.7.3 of Vaccon, 2017) are also possible. This enables a trade-off between speed, thoroughness of the reduction and loss in precision. Indeed, contrary to the F5 strategy where one has to reduce with respect to signatures, any reasonable strategy of reduction is possible.

In this section, we present the algorithm, along with proof of correctness and termination.

Algorithm 4: F4-Symbolic-Preprocessing.

```

input :  $P$ , a list of pairs of elements of  $A$ ,  $G$  a list of elements in  $A$ .
output: A Macaulay matrix
 $C \leftarrow$  the set of the monomials of the polynomials in  $P$  ;
 $U \leftarrow$  the polynomials of  $P$  ;
 $D \leftarrow \emptyset$  ;
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  $(g, \delta)$  of  $V$  with  $\delta \times g$  of biggest leading term, with tie-breaking by taking minimal  $\delta$  (for  $\leq$ ) ;
     $U \leftarrow U \cup \{\delta \times g\}$  ;
     $C \leftarrow C \cup \{\text{monomials of } \delta \times g\}$  ;
 $M \leftarrow$  the polynomials of  $U$ , written in a Macaulay matrix ;
Return  $M$  ;

```

Algorithm 5: Tropical polynomial reduction.

```

input :  $\tilde{f} \in A$ ,  $G$  a list of elements in  $A$ .
output:  $\tilde{f}$  a reduction of  $f$  by  $G$ .
 $M \leftarrow \text{F4-Symbolic-Preprocessing}(\{f\}, G)$  ;
Swap rows of  $M$  so that  $f$  corresponds to the last row of  $M$  ;
 $\tilde{M} \leftarrow \text{Tropical-LUP}(M)$ ;
 $\tilde{f} \leftarrow$  last row of  $\tilde{M}$  ;
Return  $\tilde{f}$  ;

```

7.1. Buchberger criterion and reduction

Defining algorithm for reduction in a tropical setting is not straightforward. A classical example comes from trying to use a naive adaptation of the classical polynomial reduction algorithm to reduce x by the family $G = (x + y, y + 2x)$, in $\mathbb{Q}_2[x, y]$ with $w = (0, 0)$. Even though G is a minimal Gröbner basis, the corresponding algorithm would not terminate, going through all the $2^n x$'s and $-2^n y$'s as intermediate polynomials to reduce.

Yet, we need an algorithm for reduction so as to state a Buchberger criterion, on which the correctness of F4 is based. As in Vaccon (2017), Vaccon and Yokoyama (2017), this issue can be circumvented using matrix reduction.

We begin by adapting the Symbolic-Preprocessing algorithm, removing any call for signatures. The corresponding version is presented in Algorithm 4 on page 149.

Algorithm 4 allows us to construct matrices on which we can perform reduction. Algorithm 5 on page 149 is then built upon it. It is used to define the reduction of a polynomial by a family of polynomials. It will then be used only for theoretical purpose as a way to provide a Buchberger criterion for termination of F4.

Proposition 7.1 (Buchberger's criterion). *G is a tropical Gröbner basis of $\langle G \rangle$ if and only if every S -polynomial of G reduces to zero using Algorithm 5.*

Proof. We already have the Buchberger-F5 criterion, Theorem 4.2. It is clear that Buchberger's criterion can be obtained as a weak variant of the Buchberger-F5 criterion, getting rid of the signatures. \square

7.2. An algorithm and its proof

We can now present a Tropical F4 Algorithm with Algorithm 6 on page 150.

Algorithm 6: A tropical F4 algorithm.

```

input :  $f_1, \dots, f_s$  in  $A$ 
output: A tropical GB  $G$  of  $\langle f_1, \dots, f_s \rangle$ 
 $G \leftarrow (f_1, \dots, f_s)$ ;
 $B \leftarrow \{\text{pairs of } G\}$ ;
while  $B \neq \emptyset$  do
     $d \leftarrow$  the smallest degree of an lcm of leading terms in a pair of  $B$ ;
     $P$  receives the pop of the pairs of degree  $d$  in  $B$ ;
    Write them in a Macaulay matrix  $M$ , along with their reducers obtained by F4-Symbolic-Preprocessing( $P, G$ )
    (Algorithm 4);
    Apply Algorithm 2 to compute  $\tilde{M}$  the row-echelon form of  $M$ ;
    Add to  $G$  all the polynomials obtained from  $\tilde{M}$  that provide leading monomials not in  $\{LM(g) \text{ for } g \in G\}$ ;
    Add to  $B$  the corresponding new pairs;
Return  $G$ ;

```

Proposition 7.2. *The Tropical F4 algorithm, Algorithm 6 terminates and computes a tropical GB of I .*

Proof. If Algorithm 6 does not terminate for some initial (f_1, \dots, f_s) , it means that there is an infinite sequence of polynomials $(h_i)_{i \in \mathbb{N}}$ that are added to G . Indeed, otherwise, the algorithm would terminate as it would run out of S -pairs.

For those h_i to be added in the algorithm, they have to provide an $LM(h_i)$ not already in the monomial ideal $\langle LM(g), g \in G \rangle$ for the current G . This would mean an infinite number of generator in a monomial ideal, which is a contradiction. Hence the algorithm terminates.

As for correctness, it is an application of the Buchberger criterion. After every turn in the *while* loop, all already processed S -polynomial of an S -pair reduce to 0 by G . Hence, after termination, it is the case for all the S -pairs of G and we can apply Buchberger's criterion. \square

7.3. Linear algebra and reduction

The call for Algorithm 2 in Algorithm 6 can be replaced by a call to Algorithm 3.2.2 of Vaccon (2017). When dealing with coefficients only known at finite precision, it allows the usage at each step of the best pivot available, providing a better stability.

Remark 7.3. If the input polynomials are homogeneous, the weight is $w = [0, \dots, 0]$ and one uses Algorithm 3.2.2 of Vaccon (2017), then one can show that the following behavior regarding to precision in a p -adic setting happens: loss in precision due to divisions do not accumulate.

This is not the case for affine polynomials, but one can still expect the loss in precision to often be moderate in practice.

8. Numerical experiments

A toy implementation of our algorithms in SageMath (2018) 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.³

8.1. 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 systems for varying n . Dots mean no conclusion within dozen hours.

³ Everything was performed on a Ubuntu 16.04 with 2 processors of 2.6 GHz and 16 GB of RAM.

$w=[0,\dots,0]$	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	•

8.2. Tropical 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 $2 \leq d_1 \leq d_2 \leq d_3 \leq 4$. We first compute a tropical Gröbner basis for the weight $w = [0, 0, 0]$ and the grevlex monomial ordering, and then apply an FGLM algorithm (tropical to classical as in Chapter 9 of Vaccon, 2015) 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.⁵ We can not provide a certificate on the leading monomials of the output basis though: we can not prove that no non-zero coefficient has been taken for zero due to the lack of precision in a way that impacts the computation.

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.

	$D = 4$		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

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.

	$D = 4$		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

	$D = 4$		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.

⁴ Efficiency of this choice regarding to the loss in precision was studied in the extended version of Vaccon, 2017.

⁵ By precision issue, we mean for example a loss in precision such that it is not possible to determine which term is the leading term, due to some terms of the form $O(p^N)x^\alpha$. We refer the interested reader to the Section 4 of Vaccon (2017).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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