

# Arithmetic properties related to the shuffle-product

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*Abstract<sup>1</sup>: Properties of the shuffle product in positive characteristic suggest to consider a  $p$ -homogeneous form  $\sigma : \overline{\mathbb{F}}_p\langle\langle X_1, \dots, X_k \rangle\rangle \longrightarrow \overline{\mathbb{F}}_p\langle\langle X_1, \dots, X_k \rangle\rangle$  on the vector space  $\overline{\mathbb{F}}_p\langle\langle X_1, \dots, X_k \rangle\rangle$  of formal power series in  $k$  free non-commuting variables. The form  $\sigma$  preserves rational elements in  $\overline{\mathbb{F}}_p\langle\langle X_1, \dots, X_k \rangle\rangle$ , algebraic series of  $\overline{\mathbb{F}}_p[[X]] = \overline{\mathbb{F}}\langle\langle X \rangle\rangle$  and induces a bijection on the affine subspace  $1 + \mathfrak{m}$  of formal power series with constant coefficient 1. Conjecturally, this bijection restricts to a bijection of rational elements in  $1 + \mathfrak{m} \subset \overline{\mathbb{F}}_p\langle\langle X_1, \dots, X_k \rangle\rangle$ , respectively algebraic elements in  $1 + X\overline{\mathbb{F}}_p[[X]]$ .*

## 1 Introduction

The aim of this paper is to present some properties and conjectures related to shuffle-products of power series in non-commuting variables. The shuffle product

$$A \sqcup B = \sum_{0 \leq i, j} \binom{i+j}{i} \alpha_i \beta_j X^{i+j}$$

of two power series  $A = \sum_{n=0}^{\infty} \alpha_n X^n, B = \sum_{n=0}^{\infty} \beta_n X^n \in \mathbb{K}[[X]]$  in one variable over a commutative field  $\mathbb{K}$  turns the set  $\mathbb{K}^* + X\mathbb{K}[[X]]$  into a commutative group which is not isomorphic to the commutative group on  $\mathbb{K}^* + X\mathbb{K}[[X]]$  associated to the ordinary product of (multiplicatively) invertible formal power series if  $\mathbb{K}$  is of positive characteristic. Shuffle products of rational (respectively algebraic) power series are rational (respectively algebraic). The shuffle product turns the affine subspace  $1 + X\mathbb{K}[[X]]$  into a group which is isomorphic to an infinite-dimensional  $\mathbb{F}_p$ -vector space if  $\mathbb{K}$  is a field of positive characteristic  $p$ . Rational (respectively algebraic) elements in  $1 + X\mathbb{K}[[X]]$  (or more generally in  $\mathbb{K}^* + X\mathbb{K}[[X]]$ ) form thus a group with respect to the shuffle product if  $\mathbb{K}$  is of positive characteristic.

The first interesting case is given by a subfield  $\mathbb{K} \subset \overline{\mathbb{F}}_2$  contained in the algebraic closure of the field  $\mathbb{F}_2$  with two elements. The structure of the  $\mathbb{F}_2$ -vector space induced by the shuffle product on  $1 + X\overline{\mathbb{F}}_2[[X]]$  suggests to

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consider the quadratic form

$$\begin{aligned}\sigma\left(\sum_{n=0}^{\infty}\alpha_nX^n\right) &= \sum_{n=0}^{\infty}\alpha_{2^n}^2X^{2^{n+1}} + \sum_{0\leq i\leq j}\binom{i+j}{i}\alpha_i\alpha_jX^{i+j} \\ &= \alpha_0^2 + \sum_{n=0}^{\infty}\alpha_{2^n}^2X^{2^{n+1}} + \sum_{0\leq i<j}\binom{i+j}{i}\alpha_i\alpha_jX^{i+j}.\end{aligned}$$

The quadratic form  $\sigma : \overline{\mathbb{F}_2}[[X]] \rightarrow \overline{\mathbb{F}_2}[[X]]$  thus defined preserves the vector space of rational or algebraic power series. It induces a bijection of infinite order on the affine subspace  $1 + X\overline{\mathbb{F}_2}[[X]]$ . Orbits are either infinite or of cardinality a power of two. Conjecturally, the inverse bijection  $\sigma^{-1}$  of the set  $1 + X\overline{\mathbb{F}_2}[[X]]$  preserves also rational elements and algebraic elements. We present experimental evidence for this conjecture. An analogous construction yields a homogeneous  $p$ -form (still denoted)  $\sigma : \overline{\mathbb{F}_p}[[X]] \rightarrow \overline{\mathbb{F}_p}[[X]]$  with similar properties for  $p$  an arbitrary prime.

In a second part of the paper, starting with Section 6, we recall the definition of the shuffle product for elements in the vector space  $\mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle$  of formal power series in free non-commuting variables. The shuffle product preserves again rational formal power series, characterised for instance by a Theorem of Schützenberger. The  $p$ -homogeneous form  $\sigma$  considered above has a natural extension  $\sigma : \overline{\mathbb{F}_p}\langle\langle X_1, \dots, X_k \rangle\rangle \rightarrow \overline{\mathbb{F}_p}\langle\langle X_1, \dots, X_k \rangle\rangle$ . This extension of  $\sigma$  still preserves rational elements and induces a bijection on  $1 + \mathfrak{m}$  where  $\mathfrak{m} \subset \overline{\mathbb{F}_p}\langle\langle X_1, \dots, X_k \rangle\rangle$  denotes the maximal ideal of formal power series without constant coefficient in  $\overline{\mathbb{F}_p}\langle\langle X_1, \dots, X_k \rangle\rangle$ . Conjecturally, the map  $\sigma$  restricts again to a bijection of the subset of rational elements in  $1 + \mathfrak{m}$ .

## 2 Power series in one variable

We denote by  $\mathbb{K}[[X]]$  the commutative algebra of formal power series over a commutative field  $\mathbb{K}$  with product

$$\left(\sum_{n=0}^{\infty}\alpha_nX^n\right)\left(\sum_{n=0}^{\infty}\beta_nX^n\right) = \sum_{n,m=0}^{\infty}\alpha_n\beta_mX^{n+m}$$

given by the usual (Cauchy-)product extending the product of the polynomial subalgebra  $\mathbb{K}[X] \subset \mathbb{K}[[X]]$ . Its unit group  $\mathbb{K}^* + X\mathbb{K}[[X]]$  consists of all (multiplicatively) invertible series and decomposes as a direct product  $\mathbb{K}^* \times (1 + \mathfrak{m})$  with  $\mathfrak{m} = X\mathbb{K}[[X]]$  denoting the maximal ideal of the algebra  $\mathbb{K}[[X]]$ .

A subalgebra containing the field of constants  $\mathbb{K}$  of  $\mathbb{K}[[X]]$  is *rationally closed* if it intersects the unit group  $\mathbb{K}^* + X\mathbb{K}[[X]]$  in a subgroup. The *rational closure* of a subset  $\mathcal{S} \subset \mathbb{K}[[X]]$  is the smallest rationally closed subalgebra of  $\mathbb{K}[[X]]$  which contains  $\mathcal{S}$  and the ground-field  $\mathbb{K}$ .

The rational closure of  $X$ , called the *algebra of rational fractions in  $X$*  or the *rational subalgebra* of  $\mathbb{K}[[X]]$ , contains the polynomial subalgebra  $\mathbb{K}[X]$  and is formed by all rational fractions of the form  $\frac{f}{g}$  with  $f, g \in \mathbb{K}[X], g \notin \mathfrak{m}$ . The expression  $\frac{f}{g}$  of such a rational fraction is unique if we require  $g \in 1 + \mathfrak{m}$ .

An element  $y \in \mathbb{K}[[X]]$  is *algebraic* if it satisfies a polynomial identity  $P(X, y) = 0$  for some polynomial  $P \in \mathbb{K}[X, y]$ . Algebraic series in  $\mathbb{K}[[X]]$  form a rationally closed subalgebra containing all rational fractions.

### 3 The shuffle product

The *shuffle product*, defined as

$$A \sqcup B = \sum_{n,m=0}^{\infty} \binom{n+m}{n} \alpha_n \beta_m X^{n+m}$$

for  $A = \sum_{n=0}^{\infty} \alpha_n X^n, B = \sum_{n=0}^{\infty} \beta_n X^n \in \mathbb{K}[[x]]$ , yields an associative and commutative bilinear product on the vector space  $\mathbb{K}[[x]]$  of formal power series. We call the corresponding algebra  $(\mathbb{K}[[x]], \sqcup)$  the *shuffle-algebra*. The *shuffle-group* is the associated unit group. Its elements are given by the set  $\mathbb{K}^* + X\mathbb{K}[[x]]$  underlying the multiplicative unit group and it decomposes as a direct product  $\mathbb{K}^* \times (1 + X\mathbb{K}[[x]])$ .

**Remark 3.1.** Over a field  $\mathbb{K}$  of characteristic zero, the map

$$\mathbb{K}[[X]] \ni \sum_{n=0}^{\infty} \alpha_n X^n \mapsto \sum_{n=0}^{\infty} n! \alpha_n X^n \in (\mathbb{K}[[X]], \sqcup)$$

defines an isomorphism of algebras between the usual (multiplicative) algebra of formal power series and the shuffle algebra  $(\mathbb{K}[[X]], \sqcup)$ . The shuffle product of ordinary generating series  $\sum \alpha_n X^n$  corresponds thus to the ordinary product of exponential generating series (also called divided power series or Hurwitz series, see eg. [5])  $\sum \alpha_n \frac{X^n}{n!}$ . This shows in particular the identity  $(1 - X) \sqcup (\sum_{n=0}^{\infty} n! X^n) = 1$ . The shuffle inverse of a rational fraction is thus generally transcendental in characteristic 0.

**Remark 3.2.** The inverse for the shuffle product of  $1 - a \in 1 + X\mathbb{K}[[x]]$  is given by

$$\sum_{n=0}^{\infty} a \sqcup^n = 1 + a + a \sqcup a + a \sqcup a \sqcup a + \dots$$

where  $a \sqcup^0 = 1$  and  $a \sqcup^{n+1} = a \sqcup a \sqcup^n$  for  $n \geq 1$ .

The shuffle inverse of  $1 - a \in 1 + X\mathbb{K}[[X]]$  can be computed by the recursive formulae  $B_0 = 1, C_0 = a, B_{n+1} = B_n + B_n \sqcup C_n, C_{n+1} = C_n \sqcup C_n = a \sqcup^{2^{n+1}}$  with  $B_n = \sum_{k=0}^{2^n-1} a \sqcup^k$  converging (quadratically) to the shuffle-inverse of  $1 - a$ .

**Proposition 3.3.** *The shuffle-group  $1+X\mathbb{K}[[X]]$  is isomorphic to an infinite-dimensional  $\mathbb{F}_p$ -vector-space if  $\mathbb{K}$  is a field of positive characteristic  $p$ .*

**Corollary 3.4.** *The shuffle-group  $1+X\mathbb{K}[[X]]$  is not isomorphic to the multiplicative group structure on  $1+X\mathbb{K}[[X]]$  if  $\mathbb{K}$  is of positive characteristic.*

**Proof of Proposition 3.3** We have

$$A \sqcup^p = \sum_{0 \leq i_1, i_2, \dots, i_p} \binom{i_1 + i_2 + \dots + i_p}{i_1, i_2, \dots, i_p} \alpha_{i_1} \alpha_{i_2} \dots \alpha_{i_p} X^{i_1 + \dots + i_p}.$$

for  $A = \sum_{n=0}^{\infty} \alpha_n X^n \in \mathbb{K}[[X]]$  where  $\binom{i_1 + i_2 + \dots + i_p}{i_1, i_2, \dots, i_p} = \frac{(i_1 + \dots + i_p)!}{i_1! \dots i_p!}$ . Two summands differing by a cyclic permutation of indices  $(i_1, i_2, \dots, i_p) \mapsto (i_2, i_3, \dots, i_p, i_1)$  yield the same contribution to  $A \sqcup^p$ . Over a field  $\mathbb{K}$  of positive characteristic  $p$  we can thus restrict the summation to  $i_1 = i_2 = \dots = i_p$ . Since  $\binom{ip}{i, i, \dots, i} = \frac{(ip)!}{(i!)^p} \equiv 0 \pmod{p}$  except for  $i = 0$ , we have  $A \sqcup^p = \alpha_0^p$  for  $A = \sum_{n=0}^{\infty} \alpha_n X^n \in \mathbb{K}[[X]]$ . This implies the result.  $\square$

**Remark 3.5.** *Proposition 3.3 follows also easily from Satz 1 in [7] where a different proof is given.*

**Proposition 3.6.** *Shuffle products of rational power series are rational.*

**Proof** Suppose first  $\mathbb{K}$  of characteristic zero. The result is obvious for the shuffle product of two polynomials. Extending  $\mathbb{K}$  to its algebraic closure, decomposing into simple fractions and using bilinearity, it is enough to consider shuffle products of the form  $X^h \sqcup \left( \sum_{n=0}^{\infty} n^k \alpha_n X^n \right) = \sum_{n=0}^{\infty} \binom{n+h}{h} n^k \alpha_n X^{n+h}$  which are obviously rational and shuffle products of the form

$$\left( \sum_{n=0}^{\infty} n^h \alpha_n X^n \right) \sqcup \left( \sum_{n=0}^{\infty} n^k \beta_n X^n \right) = \sum_{0 \leq m \leq n} \binom{n}{m} m^h (n-m)^k \alpha^m \beta^{n-m} X^n$$

which are evaluations at  $y = \alpha, z = \beta$  of

$$\left( y \frac{\partial}{\partial y} \right)^h \left( z \frac{\partial}{\partial z} \right)^k \left( \frac{1}{1 - (y+z)X} \right)$$

and are thus rational for  $\mathbb{K}$  of characteristic zero.

In positive characteristic, one can either consider suitable lifts into integer rings of fields of characteristic zero or deduce it as a special case of Corollary 7.3.  $\square$

**Remark 3.7.** *The proof of proposition 3.6 implies easily analyticity of shuffle products of analytic power series (defined as formal power series with strictly positive convergence radii) if  $\mathbb{K} \subset \mathbb{C}$  or  $\mathbb{K} \subset \hat{\mathbb{Q}}_p$ .*

**Proposition 3.8.** *Shuffle products of algebraic series in  $\overline{\mathbb{F}_p}[[X]]$  are algebraic.*

**Sketch of Proof** A Theorem of Christol (see Theorem 12.2.5 in [2]) states that the coefficients of an algebraic series over  $\overline{\mathbb{F}_p}$  define a  $q$ -automatic sequence with values in  $\mathbb{F}_q$  for some power  $q = p^e$  of  $p$ . Given a formal power series  $C = \sum_{n=0}^{\infty} \gamma_n X^n \in \overline{\mathbb{F}_p}[[X]]$ , we denote by  $C_{k,f}$  the formal power series  $\sum_{n=0}^{\infty} \gamma_{k+nq^f} X^n$ .

The result follows then from the observation that the series  $(A \sqcup B)_{k,f}$  are linear combination of  $A_{k_1,f} \sqcup B_{k_2,f}$  and span thus a finite-dimensional subspace of  $\overline{\mathbb{F}_p}[[X]]$  for algebraic  $A, B \in \overline{\mathbb{F}_p}[[X]]$ .  $\square$

Propositions 3.3 and 3.6 (respectively 3.3 and 3.8) imply immediately the following result:

**Corollary 3.9.** *Rational (respectively algebraic) elements of the shuffle-group  $1 + X\mathbb{K}[[X]]$  form a subgroup for  $\mathbb{K} \subset \overline{\mathbb{F}_p}$ .*

**Remark 3.10.** *A rational fraction  $A \in 1 + X\mathbb{C}[[X]]$  has a rational inverse for the shuffle-product if and only if  $A = \frac{1}{1-\lambda X}$  with  $\lambda \in \mathbb{C}$ . (Idea of proof: Decompose two rational series  $A, B$  satisfying  $A \sqcup B = 1$  into simple fractions and compute  $A \sqcup B$  using the formulae given in the proof of Proposition 3.6.)*

## 4 A quadratic form

The identity  $A \sqcup A = \alpha_0^2$  for  $A = \sum_{n=0}^{\infty} \alpha_n X^n \in \overline{\mathbb{F}_2}[[X]]$  (see the proof of Proposition 3.3) suggests to consider the quadratic map

$$\mathbb{K}[[X]] \ni A = \sum_{n=0}^{\infty} \alpha_n X^n \longmapsto \sigma(A) = \alpha_0^2 + \sum_{n=1}^{\infty} \beta_n X^n \in \mathbb{K}[[X]] \subset \overline{\mathbb{F}_2}[[X]]$$

defined by

$$\left( \sum_{n=0}^{\infty} \tilde{\alpha}_n X^n \right) \sqcup \left( \sum_{n=0}^{\infty} \tilde{\alpha}_n X^n \right) = \tilde{\alpha}_0^2 + 2 \sum_{n=0}^{\infty} \tilde{\beta}_n X^n$$

where  $\tilde{\alpha}_n$  and  $\tilde{\beta}_n$  are lifts into suitable algebraic integers of  $\alpha_n, \beta_n \in \mathbb{K} \subset \overline{\mathbb{F}_2}$ .

For  $A = \sum_{n=0}^{\infty} \alpha_n X^n$ , we get

$$\sigma(A) = \alpha_0^2 + \sum_{n=1}^{\infty} \frac{1}{2} \binom{2n}{n} \alpha_n^2 X^{2n} + \sum_{0 \leq i < j} \binom{i+j}{i} \alpha_i \alpha_j X^{i+j}$$

and  $\binom{2n}{n} \equiv 2 \pmod{4}$  if and only if  $n$  is a power of 2. This yields the formula

$$\sigma(A) = \alpha_0^2 + \sum_{n=0}^{\infty} \alpha_{2^n}^2 X^{2^{n+1}} + \sum_{0 \leq i < j} \binom{i+j}{i} \alpha_i \alpha_j X^{i+j}.$$

**Proposition 4.1.** *The formal power series  $\sigma(A)$  is rational (respectively algebraic) if  $A \in \overline{\mathbb{F}_2}[[X]]$  is rational (respectively algebraic).*

The statement of this proposition in the case of a rational series is a particular case of Proposition 8.1.

Proposition 4.1 can be proven by modifying slightly the arguments used in the proof of Propositions 3.6 and 3.8 and by applying them to a suitable integral lift  $\tilde{A} \in \overline{\mathbb{Q}}[[X]]$  of  $A$ .  $\square$

Finally, one has also the following result whose easy proof is left to the reader:

**Proposition 4.2.** *The quadratic form  $A \mapsto \sigma(A)$  commutes with the Frobenius map  $A \mapsto A^2$ .*

#### 4.1 The main conjecture

**Proposition 4.3.** *The quadratic form  $A \mapsto \sigma(A)$  induces a bijection on the affine subspace  $1 + X\mathbb{K}[[X]]$  for a subfield  $\mathbb{K} \subset \overline{\mathbb{F}_2}$ .*

**Remark 4.4.** *Omitting the restriction to  $1 + X\mathbb{K}[[X]]$ , the quadratic form  $\sigma$  is neither surjective nor injective: One has  $\sigma^{-1}(X) = \emptyset$  and  $\sigma(A) = 0$  if  $A \in X^3\overline{\mathbb{K}}[[X^2]]$ . (The example for non-injectivity is related to the easy observation that  $\sigma(A) = 0$  if and only if  $\sigma(1 + A) = 1 + A$  for  $A \in \overline{\mathbb{F}_2}[[X]]$ .)*

**Proof of Proposition 4.3** This follows from the identity

$$\sigma(A) - \sigma(B) = (\alpha_n - \beta_n)X^n + X^{n+1}\overline{\mathbb{F}_2}[[X]]$$

if  $A = 1 + \sum_{n=1}^{\infty} \alpha_n X^n, B = 1 + \sum_{n=1}^{\infty} \beta_n X^n$  coincide up to  $X^{n-1}$  (ie. if  $\alpha_j = \beta_j$  for  $j = 1, \dots, n-1$ ).  $\square$

Experimental evidence (see Sections 4.5, 4.6 and 4.7 for a few exemples) suggests the following conjecture:

**Conjecture 4.5.** *If  $A \in 1 + \overline{\mathbb{F}_2}[[X]]$  is rational (respectively algebraic) then its preimage  $\sigma^{-1}(A) \in 1 + \overline{\mathbb{F}_2}[[X]]$  is rational (respectively algebraic).*

This conjecture, in the case of rational power series, is a particular case of Conjecture 8.2 (which has, to my knowledge, no algebraic analogue).

**Remark 4.6.** *There is perhaps some hope for proving this conjecture in the rational case using the formulae of the proof of Proposition 3.6: Considering integral lifts into suitable algebraic integers and assuming a bound on the degrees of the numerator and denominator of  $\sigma^{-1}(A)$  (for rational  $A \in 1 + X\overline{\mathbb{F}_2}[[X]]$ ) one gets a system of algebraic equations whose reduction modulo 2 should have a solution.*

## 4.2 Orbits in $1 + X\overline{\mathbb{F}_2}[[X]]$ under $\sigma$

The purpose of this Section is to describe a few properties of the bijection defined by  $\sigma$  on  $1 + X\overline{\mathbb{F}_2}[[X]]$ .

**Proposition 4.7.** (i) *The orbit of  $A \in 1 + X\overline{\mathbb{F}_2}[[X]]$  is infinite if it involves a monomial of the form  $X^{2^k}$ .*

(ii) *The orbit of a polynomial  $A \in 1 + X\overline{\mathbb{F}_2}[X]$  is finite if it involves no monomial of the form  $X^{2^k}$ .*

(iii) *The cardinal of every finite orbit in  $1 + X\overline{\mathbb{F}_2}[[X]]$  of  $\sigma$  is a power of 2.*

**Remark 4.8.** (i) *All elements of the form  $1 + X^3\overline{\mathbb{F}_2}[[X^2]]$  are fixed by  $\sigma$ , cf. Remark 4.4.*

(ii) *The algebraic function  $A = 1 + \sum_{n=0}^{\infty} X^{3 \cdot 4^n}$  (satisfying the equation  $A + A^4 + X^3 = 0$ ) contains no monomial of the form  $X^{2^k}$  and has infinite orbit under  $\sigma$ . I ignore if the affine subspace  $1 + X\overline{\mathbb{F}_2}[[X]]$  contains an infinite orbit formed by rational fractions without monomials of the form  $X^{2^k}$ .*

**Proof of Proposition 4.7** Associate to  $A = 1 + \sum_{n=1}^{\infty} \alpha_n X^n \in \overline{\mathbb{F}_2}[[X]]$  the auxiliary series  $P_A = \sum_{n=0}^{\infty} \alpha_{2^n} t^n \in \mathbb{F}_2[[t]]$ . It is easy to check that  $P_{\sigma^k(A)} = (1+t)^k P_A$  for all  $k \in \mathbb{Z}$ . This implies assertion (i).

Consider a polynomial  $A$  containing only coefficients of degree  $< 2^n$  and no coefficient of degree a power of 2. The formula for  $\sigma(A)$  shows that  $\sigma(A)$  satisfies the same conditions. This implies that the orbit of  $A$  under  $\sigma$  is finite and proves assertion (ii).

If  $A \in 1 + \overline{\mathbb{F}_2}[[X]]$  is such that  $\sigma^{2^k}(A) \equiv A \pmod{X^{N-1}}$ , then  $\sigma^{2^k}(A + X^N) = \sigma^{2^k}(A) + X^N \pmod{X^{N+1}}$ . This implies easily the last assertion.  $\square$

## 4.3 A variation

The series  $P_A = \sum_{n=0}^{\infty} \alpha_{2^n} t^n$  associated to an algebraic power series  $A = \sum_{n=0}^{\infty} \alpha_n X^n \in \overline{\mathbb{F}_2}[[X]]$  as in the proof of proposition 4.7 is always ultimately periodic and thus rational. This implies algebraicity of  $\sum_{n=0}^{\infty} \alpha_{2^n} X^{2^{n+1}}$  for algebraic  $\sum_{n=0}^{\infty} \alpha_n X^n \in \overline{\mathbb{F}_2}[[X]]$ . The properties of the quadratic form

$$A = \sum_{n=0}^{\infty} \alpha_n X^n \longmapsto \tilde{\sigma}(A) = \sum_{0 \leq i \leq j} \binom{i+j}{i} \alpha_i \alpha_j X^{i+j}$$

with respect to algebraic elements in  $\overline{\mathbb{F}_2}[[X]]$  should thus be somewhat similar to the properties of  $\sigma$ . In particular  $\tilde{\sigma}$  preserves algebraic series and induces a bijection on  $1 + X\overline{\mathbb{F}_2}[[X]]$  which is of infinite order. Orbits are either infinite or finite and the cardinality of a finite orbit is a power of 2. Conjecture 4.5 (if true), together with Proposition 3.8, would imply that  $\tilde{\sigma}^{-1}(A)$  is algebraic for algebraic  $A \in 1 + X\overline{\mathbb{F}_2}[[X]]$ . Remark however that

$\tilde{\sigma}(A)$  is in general not rational for rational  $A \in 1 + X\overline{\mathbb{F}_2}[[X]]$ : An easy computation shows indeed that  $\tilde{\sigma}(\frac{1}{1+X}) = 1 + \sum_{n=0}^{\infty} X^{2^n}$  which satisfies the algebraic equation  $y + y^2 + X = 0$  but is irrational since coefficients of rational power series over (the algebraic closure of) finite fields are ultimately periodic. On the other hand,  $\tilde{\sigma}^{-1}(\frac{1}{1+X})$  is the irrational algebraic series  $y = 1 + X + X^2 + X^4 + X^7 + \dots \in \mathbb{F}_2[[X]]$  satisfying the equation

$$X + (1 + X + X^2)y + (1 + X^2 + X^4)y^3 = 0.$$

The quadratic map  $\tilde{\sigma}$  behaves however better than  $\sigma$  with respect to polynomials: One can show easily that it induces a bijection of order a power of 2 (depending on  $n$ ) on polynomials of degree  $< 2^n$  in  $1 + X\overline{\mathbb{F}_2}[[X]]$ .

**Remark 4.9.** *The definition of the quadratic forms  $\sigma$  and  $\tilde{\sigma}$  suggests to consider the quadratic form  $\psi(\sum_{n=0}^{\infty} \alpha_n X^n) = \sum_{i \leq j} \alpha_i \alpha_j X^{i+j}$  of  $\overline{\mathbb{F}_2}[[X]]$ . Using the fact that rational elements of  $\overline{\mathbb{F}_2}[[X]]$  have ultimately periodic coefficients, it is not hard to show that  $\psi$  preserves rationality. It is also easy to show that  $\psi$  induces a bijection on  $1 + X\overline{\mathbb{F}_2}[[X]]$ . However, the preimage  $\psi^{-1}(1 + X) \in \mathbb{F}_2[[X]]$  is apparently neither rational nor algebraic.*

#### 4.4 Algorithmic aspects

The *integral Thue-Morse* function  $tm(\sum_{j=0}^{\infty} \epsilon_j 2^j) = \sum_j \epsilon_j$  is defined as the digit sum of a natural binary integer  $n = \sum_{j=0}^{\infty} \epsilon_j 2^j \in \mathbb{N}$ . Setting  $tm(0) = 0$ , it can then be computed recursively by  $tm(2n) = tm(n)$  and  $tm(2n+1) = 1 + tm(n)$ . Kummer's equality  $\binom{i+j}{i} \equiv 2^{tm(i)+tm(j)-tm(i+j)} \pmod{2}$  (which follows also from a Theorem of Lucas, see page 422 of [2]), allows a fast computation of binomial coefficients modulo 2. We have thus

$$\begin{aligned} \sigma(A) &= \alpha_0^2 + \sum_{n=0}^{\infty} \alpha_{2^n}^2 X^{2^{n+1}} + \sum_{0 \leq i < j} \binom{i+j}{i} \alpha_i \alpha_j X^{i+j} \\ &= \alpha_0^2 + \sum_{n=0}^{\infty} \alpha_{2^n}^2 X^{2^{n+1}} + \sum_{0 \leq i < j, \, tm(i+j)=tm(i)+tm(j)} \alpha_i \alpha_j X^{i+j} \end{aligned}$$

for  $A = \sum_{n=0}^{\infty} \alpha_n X^n \in \mathbb{F}_2[[x]]$ . The last formula is suitable for computations.

The preimage  $\sigma^{-1}(A)$  of  $A \in 1 + X\overline{\mathbb{F}_2}[[X]]$  can be computed iteratively as the unique fixpoint in  $\overline{\mathbb{F}_2}[[X]]$  of the map

$$Z \longmapsto Z + A - \sigma(Z).$$

Starting with an arbitrary initial value  $Z_0$  (eg. with  $Z_0 = A$ ), the sequence  $Z_0, Z_1, \dots, Z_{n+1} = Z_n + A - \sigma(Z_n), \dots \in \overline{\mathbb{F}_2}[[X]]$  converges quadratically (roughly doubling the number of correct coefficients at each iteration) with limit the attractive fixpoint  $\sigma^{-1}(A)$ .



#### 4.4.1 Checking identities in the rational case

Define the degree of a non-zero rational fraction  $A = \frac{f}{g} \in \overline{\mathbb{F}_2}[[X]]$  with  $f \in \overline{\mathbb{F}_2}[X], g \in 1 + \overline{\mathbb{F}_2}[X]$  coprime, by  $\deg(A) = \max(\deg(f), \deg(g))$ . Proposition 8.1 and Remark 7.1 imply the equality

$$\deg(\sigma(A)) \leq 1 + \binom{\deg(A) + 2}{2}.$$

This inequality can be used to prove identities of the form  $\sigma(A) = B$  involving two rational fractions  $A, B \in \overline{\mathbb{F}_2}[X]$  by checking equality of the first  $2 + \binom{\deg(A)+2}{2} + \deg(B)$  coefficients of the series  $\sigma(A)$  and  $B$ .

#### 4.4.2 Checking identities in the algebraic case

Given a power series  $A = \sum_{n=0}^{\infty} \alpha_n X^n \in \overline{\mathbb{F}_2}[[X]]$ , we consider the power series  $A_{k,f} = \sum_{n=0}^{\infty} \alpha_{k+n \cdot 2^f} X^n$  for  $k, f \in \mathbb{N}$  such that  $0 \leq k < 2^f$ . The vector space  $\mathcal{K}(A)$  (called the 2-kernel of  $A$ , see [2]) spanned by all series  $A_{k,f}$  is finite-dimensional if and only if  $A$  is algebraic and one has the inequality

$$\dim(\mathcal{K}(\sigma(A))) \leq 1 + \binom{1 + \dim(\mathcal{K}(A))}{2}.$$

This inequality, together with techniques of [3], reduces the proof of equalities  $\sigma(A) = B$  involving algebraic series  $A, B \in \overline{\mathbb{F}_2}[[X]]$  to the equality among finite series developpements of sufficiently high order  $N$  (depending on combinatorial properties) of  $A$  and  $B$ . The typical value for  $N$  is of order  $2^{2 + \binom{1 + \dim(\mathcal{K}(A))}{2}}$  and is thus unfortunately of no practical use in many cases.

### 4.5 Examples involving rational fractions in $1 + \mathbb{F}_2[[X]]$

#### 4.5.1 A few preimages of polynomials

$$\begin{aligned} \sigma^{-1}(1+X) &= \frac{1}{1+X}, \sigma^{-1}((1+X)^3) = 1+X+X^3, \sigma^{-1}((1+X)^5) = (1+X)^2(1+X+X^2)(1+X^2+X^3), \\ \sigma^{-1}((1+X)^7) &= \frac{1+X^3+X^6}{(1+X)^7}, \sigma^{-1}((1+X)^9) = (1+X)^6(1+X+X^9), \sigma^{-1}(1+X+X^2) = 1+X, \\ \sigma^{-1}(1+X^2+X^3) &= \frac{1+X^2+X^3}{(1+X)^4}, \sigma^{-1}(1+X+X^3) = \frac{1+X+X^2}{(1+X)^4}, \\ \sigma^{-1}(1+X+X^4) &= 1+X+X^2+X^3, \sigma^{-1}(1+X^3+X^4) = \frac{1+X+X^2}{(1+X)^3}, \\ \sigma^{-1}(1+X+X^2+X^3+X^4) &= \frac{1+X+X^3}{(1+X)^4}, \sigma^{-1}(1+X+X^2+X^3+X^5) = (1+X)(1+X^3+X^4), \\ \sigma^{-1}(1+X+X^3+X^4+X^5) &= (1+X+X^2+X^5+X^7), \sigma^{-1}(1+X^2+X^3+X^4+X^5) = (1+X+X^3)(1+X+X^4), \\ \sigma^{-1}(1+X^2+X^5) &= \frac{(1+X+X^2)(1+X+X^3)}{(1+X)^6}, \sigma^{-1}(1+X+X^2+X^4+X^5) = \frac{(1+X+X^4)}{(1+X)^8}, \\ \sigma^{-1}((1+X+X^2)^3) &= \frac{1+X^2+X^3}{(1+X)^7}, \sigma^{-1}((1+X)(1+X+X^2)) = (1+X)(1+X+X^2), \\ \sigma^{-1}((1+X)^2(1+X+X^2)) &= (1+X+X^2), \sigma^{-1}((1+X)^3(1+X+X^2)) = \frac{1+X^3+X^4}{(1+X)^6}, \\ \sigma^{-1}((1+X)^4(1+X+X^2)) &= \frac{1+X+X^4+X^6+X^7}{(1+X)^8}, \end{aligned}$$

These examples suggest the following conjecture:

**Conjecture 4.10.** For  $P \in 1 + X\mathbb{F}_2[X]$  a polynomial of degree  $\leq 2^k$ , we have  $\sigma^{-1}(P) = \frac{Q_P}{(1+X)^{\alpha_P}}$  with  $0 \leq \alpha_P \leq 2^k$  and  $Q_P \in 1 + X\mathbb{F}_2[X]$  a polynomial of degree  $< 2^k$ .

#### 4.5.2 A few examples of rational fractions

$$\begin{aligned}\sigma^{-1}\left(\frac{1}{(1+X)^3}\right) &= \frac{(1+X)^2(1+X+X^4)}{(1+X+X^2)^4}, \sigma^{-1}\left(\frac{1}{1+X+X^2}\right) = \frac{(1+X)^3}{1+X^3+X^4}, \sigma^{-1}\left(\frac{1+X}{1+X+X^2}\right) = \\ &= \frac{(1+X)^2}{1+X^3+X^4}, \sigma^{-1}\left(\frac{1+X+X^2}{1+X}\right) = \frac{1+X}{1+X+X^2}, \sigma^{-1}\left(\frac{1+X+X^2}{(1+X)^2}\right) = \frac{1+X+X^3}{(1+X)^2}, \sigma^{-1}\left(\frac{1+X+X^2}{(1+X)^3}\right) = \\ &= \frac{1+X^3+X^7}{(1+X+X^2)^4}, \sigma^{-1}\left(\frac{1+X+X^2}{(1+X)^4}\right) = \frac{(1+X+X^3)(1+X^3+X^4)}{(1+X+X^2)^4}, \\ \sigma^{-1}\left(\frac{1+X+X^2}{(1+X)^5}\right) &= \frac{1+X+X^2+X^3+X^4+X^5+X^6+X^{12}+X^{13}}{(1+X+X^2)^7}, \sigma^{-1}\left(\frac{(1+X+X^2)^2}{1+X}\right) = \frac{1+X+X^2+X^3+X^4}{(1+X+X^2)^4}, \\ \sigma^{-1}\left(\frac{(1+X+X^2)^2}{(1+X)^3}\right) &= \frac{(1+X+X^2)(1+X^2+X^5)}{(1+X)^4}.\end{aligned}$$

#### 4.6 A few iterations of $\sigma$ and $\sigma^{-1}$ on rational fractions in $1 + X\mathbb{F}_2[X]$

##### 4.6.1 Example

Iterating  $\sigma^{-1}$  on  $1 + X$  yields the following rational fractions given by their simplest expression, corresponding not necessarily to the complete factorisation into irreducible polynomials of their numerators and enumerators (such a factorisation makes sense when working in the multiplicative algebra  $\mathbb{F}_2[[X]]$  and is probably irrelevant for the map  $\sigma$ , related to the shuffle algebra structure  $(\mathbb{F}_2[[X]], \sqcup)$ ).

$$\begin{aligned}\sigma^{-1}(1+X) &= \frac{1}{1+X} \\ \sigma^{-2}(1+X) &= \frac{1}{1+X+X^2} \\ \sigma^{-3}(1+X) &= \frac{(1+X)^3}{1+X^3+X^4} \\ \sigma^{-4}(1+X) &= \frac{1+X+X^4+X^5+X^7}{1+X^4+X^6+X^7+X^8} \\ \sigma^{-5}(1+X) &= \frac{1+X+X^2+X^3+X^4+X^5+X^7+X^8+X^{14}}{1+X^{15}+X^{16}} \\ \sigma^{-6}(1+X) &= \frac{(1+X)^2(1+X+X^2+X^{14}+X^{17}+X^{20}+X^{21}+X^{24}+X^{25}+X^{26}+X^{29})}{1+X^{16}+X^{30}+X^{31}+X^{32}}\end{aligned}$$

### 4.6.2 Example

Iterating  $\sigma^{-1}$  or  $\sigma$  on  $\frac{1+X+X^2}{(1+X)^2} = 1 + X + X^3 + X^5 + X^7 + \dots$  yields the following (not necessarily completely factored) results:

$$\begin{aligned}
\sigma^{-4} \left( \frac{1+X+X^2}{(1+X)^2} \right) &= \frac{1+X+X^3+X^5+X^6+X^8+X^9+X^{10}+X^{13}+X^{14}}{1+X^8+X^{12}+X^{14}+X^{16}} \\
\sigma^{-3} \left( \frac{1+X+X^2}{(1+X)^2} \right) &= \frac{1+X+X^2+X^3+X^5}{(1+X^3+X^4)^2} \\
\sigma^{-2} \left( \frac{1+X+X^2}{(1+X)^2} \right) &= \frac{(1+X)^3}{(1+X+X^2)^2} \\
\sigma^{-1} \left( \frac{1+X+X^2}{(1+X)^2} \right) &= \frac{1+X+X^3}{(1+X)^2} \\
\sigma^1 \left( \frac{1+X+X^2}{(1+X)^2} \right) &= \frac{1+X+X^4}{(1+X)^2} \\
\sigma^2 \left( \frac{1+X+X^2}{(1+X)^2} \right) &= \frac{1+X+X^8}{(1+X)^4} \\
\sigma^3 \left( \frac{1+X+X^2}{(1+X)^2} \right) &= \frac{1+X+X^2+X^4+X^{10}+X^{12}+X^{16}}{(1+X)^8} \\
\sigma^4 \left( \frac{1+X+X^2}{(1+X)^2} \right) &= \frac{1+X+X^3+X^5+X^6+X^{10}+X^{11}+X^{12}+X^{13}+X^{22}+X^{26}+X^{28}+X^{32}}{(1+X)^{16}}
\end{aligned}$$

### 4.6.3 Example

Iterating  $\sigma^{-1}$  on  $\frac{1}{1+X+X^3}$  yields the following (not necessarily completely factored) rational fractions:

$$\begin{aligned}
\sigma^{-3} \left( \frac{1}{1+X+X^3} \right) &= \frac{(1+X+X^2+X^4+X^6+X^{12}+X^{15})(1+X^2+X^5+X^6+X^{10}+X^{12}+X^{15})}{1+X^{24}+X^{28}+X^{31}+X^{32}} \\
\sigma^{-2} \left( \frac{1}{1+X+X^3} \right) &= \frac{1+X+X^2+X^3+X^5+X^8+X^{10}+X^{11}+X^{15}}{1+X^8+X^{14}+X^{15}+X^{16}} \\
\sigma^{-1} \left( \frac{1}{1+X+X^3} \right) &= \frac{(1+X)^5}{1+X^7+X^8} \\
\sigma^1 \left( \frac{1}{1+X+X^3} \right) &= \frac{1+X+X^2+X^3+X^4}{1+X^2+X^3} \\
\sigma^2 \left( \frac{1}{1+X+X^3} \right) &= \frac{1+X+X^2+X^3+X^4+X^6+X^8}{(1+X^2+X^3)^2} \\
\sigma^3 \left( \frac{1}{1+X+X^3} \right) &= \frac{1+X+X^4+X^5+X^6+X^8+X^9+X^{10}+X^{12}+X^{13}+X^{14}+X^{16}}{(1+X^2+X^3)^4} \\
\sigma^4 \left( \frac{1}{1+X+X^3} \right) &= \frac{P_4}{(1+X^2+X^3)^8}
\end{aligned}$$

**Remark 4.11.** Define the degree of a rational fraction  $A \in \mathbb{F}_2[[x]]$  as  $\deg(A) = \max(\deg(f), \deg(g))$  if  $A = \frac{f}{g}$  with  $f, g \in \mathbb{F}_2[x]$  without common factor. For rational  $A \in 1 + X\mathbb{F}_2[[X]]$  we have  $\lim_{n \rightarrow \pm\infty} \frac{1}{|n|} \log(\deg(\sigma^n A)) = 0$  if the orbit of  $A$  under  $\sigma$  is finite. The three examples of Section 4.6 suggest that this limit exists (and equals  $\log(2)$ ) for these examples). It would be interesting to prove the existence of this limit (or to exhibit a counterexample) for an arbitrary rational fraction  $A \in 1 + \mathbb{F}_2[[X]]$ . Since we have clearly  $\lim_{n \rightarrow \infty} \frac{1}{n} \log(\deg(\sigma^n(A))) = \log(2)$  for  $A \in \mathbb{F}_2[X]$  a polynomial with infinite orbit, one can also ask for the existence of values other than  $0, \log(2)$  for this limit which defines obviously an invariant of orbits under the bijection  $\sigma$  on rational fractions in  $1 + \mathbb{F}_2[[X]]$ .

## 4.7 Examples with algebraic series in $1 + X\mathbb{F}_2[[X]]$

An algebraic power series  $A = \sum_{n=0}^{\infty} \alpha_n X^n \in \overline{\mathbb{F}_2}[[X]]$  can be conveniently described by a basis of the finite-dimensional vector space  $\mathcal{K}(A)$  introduced in Section 4.4.2. More precisely, given a word  $\epsilon_1 \dots \epsilon_l \in \{0, 1\}^l$  of finite length  $l \in \mathbb{N}$ , we consider the power series

$$A_{\epsilon_1, \dots, \epsilon_l} = \sum_{n=0}^{\infty} \alpha_{n2^l + \sum_{j=1}^l \epsilon_j 2^{j-1}} X^n.$$

Properties of the Frobenius map imply the identity

$$A_{\epsilon_1, \dots, \epsilon_l} = A_{\epsilon_1, \dots, \epsilon_l 0}^2 + X A_{\epsilon_1, \dots, \epsilon_l 1}^2.$$

The expression of these identities in terms of a basis for  $\mathcal{K}(A)$  gives a fairly compact descriptions for algebraic series in  $\mathbb{F}_2[[X]]$  as illustrated by a few examples below.

A minimal polynomial of an algebraic series  $A \in \mathbb{F}_2[[X]]$  can be of degree  $2^{\dim(\mathcal{K}(A))}$  in the variable  $A$ . One can recover such a minimal polynomial for  $A$  by applying an algorithm for Gröbner bases to the identities described above associated to polynomial relations in  $\mathcal{K}(A)$  (in terms of a basis or of a generating set).

### 4.7.1 Example

The preimage  $z = \sigma^{-1}(1 + \sum_{n=0}^{\infty} X^{2^n})$  satisfies the polynomial equation  $1 + (1 + X)z^3 = 0$ .

### 4.7.2 Example

Consider the algebraic series  $y = 1 + \sum_{n=0}^{\infty} X^{3 \cdot 4^n}$  satisfying  $y + y^4 + X^3 = 0$  already considered in Remark 4.8. The series  $z = \sigma^{-1}(y)$  satisfies the algebraic equation  $1 + (1 + X^3)z^3$ .

### 4.7.3 Example

Consider the algebraic power series  $y = \sum_{n=0}^{\infty} X^{2^n-1} = 1 + X + X^3 + X^7 + X^{15} + X^{31} + \dots \in \mathbb{F}_2[[X]]$  satisfying the polynomial equation  $1 + y + Xy^2 = 0$ . The formal power series  $z = \sigma^{-1}(y) = 1 + X + X^2 + \dots$  satisfies the algebraic equation

$$1 + X^2 + X^3 + (1 + X)^4 z + X(1 + X)^4 z^2 = 0$$

and is given by

$$z = \frac{1}{1 + X} + X^3 \left( \sum_{n=0}^{\infty} (tm(n) + tm(n+1)) X^n \right)^4 \in \mathbb{F}_2[[X]]$$

where  $tm\left(\sum_{j=0} \epsilon_j 2^j\right) = \sum_{j=0} \epsilon_j$  is the Thue-Morse sequence (see also [1] for the sequence  $n \mapsto tm(n) + tm(n+1) \pmod{2}$ ).

**Remark 4.12.** For all  $n \in \mathbb{N}$ , one can show that  $\sigma^n(y) = y + P_n(X)$  with  $P_n(X) \in \mathbb{F}_2[[X]]$  a polynomial where  $y = \sum_{n=0}^{\infty} X^{2^n-1}$ . (The series  $\sigma^n(y)$  is of course algebraic for all  $n \in \mathbb{N}$ , see Proposition 4.1.)

#### 4.7.4 Example

Consider the algebraic power series  $y = \sum_{n=0}^{\infty} tm(n+1)X^n = 1 + x + x^3 + x^6 + \dots \in \mathbb{F}_2[[X]]$  (satisfying  $(1 + (1+x)^2)y + x(1+x)^3y^2 = 0$ ) related to the Thue-Morse sequence. The preimage  $z = \sigma^{-1}(y)$  yields the algebraic system of equations

$$\begin{aligned} z &= z_0^2 + Xz_1^2 \\ z_0 &= z_0^2 + Xz_{01}^2 \\ z_1 &= z_{10}^2 + Xz_{11}^2 \\ z_{01} &= z_{01}^2 + X(z_0 + z_{10})^2 \\ z_{10} &= z_{10}^2 + X(z_0 + z_1 + z_{01} + z_{11})^2 = z_1 + X(z_0 + z_1 + z_{01})^2 \\ z_{11} &= (z_1 + z_{10} + z_{11})^2 + X(z_{01} + z_{10} + z_{11})^2 = z_1 + (z_1 + z_{11})^2 + X(z_{01} + z_{10})^2 \end{aligned}$$

#### 4.7.5 Example

Consider the algebraic series  $y = \sigma^{-1}\left(\sum_{n=0}^{\infty} (tm(n) + tm(n+1))X^n\right) \in \mathbb{F}_2[[X]]$  (satisfying  $1 + (1+X)y + X(1+X)y^2 = 0$ ). The preimage  $z = \sigma^{-1}(y) \in \mathbb{F}_2[[X]]$  satisfies the algebraic system of equations:

$$\begin{aligned} z &= z_0^2 + Xz_1^2, \\ z_0 &= z_{00}^2 + Xz_0^2, \\ z_1 &= Xz_{11}^2, \\ z_{00} &= z_0^2 + X(z_0 + z_{00})^2, \\ z_{11} &= z_{00}^2 + X(z_0 + z_1 + z_{00})^2 \end{aligned}$$

which, together with the constant terms  $z(0) = z_0(0) = z_{00}(0) = z_{11}(0) = 1, z_1(0) = 0$ , determines the series  $z, z_0 = \frac{1}{1+X+X^2}, z_1, z_{00} = \frac{1+X}{1+X+X^2}, z_{11} = z + \frac{X^2(1+X)}{(1+X+X^2)^2}$  uniquely. Eliminating the series  $z_0, z_1, z_{00}, z_{11}$  by Gröbner-basis techniques yields the algebraic equation

$$1 + X^2 + X^6 + X^{10} + X^{11} + X^{12} + X^{15} + (1+X+X^2)^8 z + X^3(1+X+X^2)^8 z^4 = 0$$

for  $z$ .

#### 4.7.6 Example

The series  $y = \sum_{n=0}^{\infty} \binom{3n}{n} X^n \in \mathbb{F}_2[[X]]$  satisfies the algebraic equation  $y = 1 + Xy^3$  (cf. page 423 of [2]). Its preimage  $z = \sigma^{-1}(y)$  gives rise to the

algebraic system

$$\begin{aligned}
z &= z_0^2 + Xz_1^2, \\
z_0 &= z^2 + Xz_{01}^2, \\
z_1 &= z_{10}^2 + Xz_{11}^2, \\
z_{01} &= z_{010}^2 + Xz_{011}^2, \\
z_{10} &= (z_0 + z_{010})^2 + Xz_{011}^2 &= z_{01} + z_0^2, \\
z_{11} &= z_{010}^2 &= (1+X)^2 z^4 + z_1^2, \\
z_{010} &= (z + z_{10})^2 + X(z + z_{11})^2 &= (1+X)z^2 + z_1, \\
z_{011} &= (z + z_{10})^2 + X(z_{01} + z_{10})^2
\end{aligned}$$

## 5 Other primes

There exists an analogue of the quadratic map  $\sigma : \overline{\mathbb{F}_2}[[x]] \longrightarrow \overline{\mathbb{F}_2}[[x]]$  for  $p$  an arbitrary prime. It corresponds to the  $p$ -homogenous form (still denoted)  $\sigma : \overline{\mathbb{F}_p}[[X]] \longrightarrow \overline{\mathbb{F}_p}[[X]]$  defined by

$$\sigma(A) \equiv \tilde{\alpha}_0^p + \sum_{n=1}^{\infty} \tilde{\beta}_n X^n \pmod{p}$$

for  $A = \sum_{n=0}^{\infty} \alpha_n X^n \in \overline{\mathbb{F}_p}[[X]]$  with  $\sum_{n=1}^{\infty} \tilde{\beta}_n X^n \in X\overline{\mathbb{Q}}[[X]]$  given by the equality

$$\tilde{A} \sqcup^p = \tilde{\alpha}_0^p + p \left( \sum_{n=1}^{\infty} \tilde{\beta}_n X^n \right)$$

for  $\tilde{A} \in \overline{\mathbb{Q}}[[X]]$  an integral lift of  $A \equiv \tilde{A} \pmod{p}$ .

The  $p$ -homogeneous form  $\sigma$  restricts to a bijection of  $1 + X\overline{\mathbb{F}_p}[[X]]$  and shares most properties holding for  $p = 2$ . In particular, we have:

**Proposition 5.1.** *The formal power series  $\sigma(A)$  is rational (respectively algebraic) if  $A \in \overline{\mathbb{F}_p}[[X]]$  is rational (respectively algebraic).*

**Conjecture 5.2.** *If  $A \in 1 + \overline{\mathbb{F}_p}[[X]]$  is rational (respectively algebraic) then its preimage  $\sigma^{-1}(A)$  is rational (respectively algebraic).*

### 5.1 A few examples for $p = 3$

Values of  $\sigma^{-1}(A) \in \overline{\mathbb{F}_3}[[X]]$  for a few rational  $A \in 1 + X\overline{\mathbb{F}_3}[[X]]$  are:

$$\begin{aligned}
\sigma^{-1}(1+X) &= \frac{1}{1-X}, \quad \sigma^{-1}((1+X)^2) = \frac{1-X-X^2}{(1+X)^3}, \quad \sigma^{-1}\left(\frac{1}{1+X}\right) = \frac{(1+X)^2}{1-X^2+X^3}, \\
\sigma^{-1}\left(\frac{1}{(1+X)^2}\right) &= \frac{1+X+X^2-X^4+X^5+X^7+X^8}{(1-X^2+X^3)^3}, \quad \sigma^{-1}\left(\frac{1+X}{1-X}\right) = \frac{1-X-X^2}{1-X^2+X^3}, \quad \sigma^{-1}\left(\frac{1+X}{1+X^2}\right) = \\
&= \frac{(1-X)^2}{(1+X)(1-X-X^2)}.
\end{aligned}$$

### 5.1.1 Two algebraic examples for $p = 3$

The algebraic series  $\sum_{n=0}^{\infty} X^{3^n-1} = 1 + X^2 + X^8 + X^{26} + \dots$  is fixed by  $\sigma$ .

The preimage  $z = \sigma^{-1}(1 + \sum_{n=0}^{\infty} X^{3^n})$  satisfies the polynomial equation  $(1 + X)^3(1 - X)z^{13} - 1$ . (The power series  $y = 1 + \sum_{n=0}^{\infty} X^{3^n} \in \mathbb{F}_3[[X]]$  satisfies the algebraic equation  $y = X + y^3$ .)

### 5.2 A few rational examples for $p = 5$

We give here values of  $\sigma^{-1}(A) \in \mathbb{F}_5[[X]]$  for a few rational  $A \in 1 + X\mathbb{F}_5[[X]]$ :

$$\begin{aligned} \sigma^{-1}(1 + X) &= \frac{1}{1-X}, \quad \sigma^{-1}((1 + X)^2) = \frac{(1-X)(1+2X)(1+X+X^2)}{(1-2X)^5}, \quad \sigma^{-1}((1 + X)^3) = \frac{(1-2X)(1+2X^2-X^3)}{(1+2X)^5}, \\ \sigma^{-1}\left(\frac{1}{1+X}\right) &= \frac{(1-2X)(1+X-X^2-2X^3)}{1-X^4+X^5}, \quad \sigma^{-1}\left(\frac{1}{(1+X)^2}\right) = \frac{1-2X+2X^2+2X^4+2X^5-2X^6-2X^7-X^8+X^9+X^{11}-2X^{13}-2X^{14}-2X^{15}-X^{16}+X^{18}+X^{19}-2X^{21}+X^{24}}{(1-X^4+X^5)^5}, \\ \sigma^{-1}\left(\frac{1+X}{1-X}\right) &= \frac{1+2X+X^2+2X^3-2X^4}{1-X^4-2X^5}, \quad \sigma^{-1}\left(\frac{1+X}{1-2X}\right) = \frac{1-2X-2X^3}{1-X^4+2X^5}, \quad \sigma^{-1}\left(\frac{1+X}{1+2X}\right) = \frac{1-X-2X^2-X^3-2X^4}{1-X^4+X^5}. \end{aligned}$$

## 6 Power series in free non-commuting variables

This and the next section recall a few basic and well-known facts concerning (rational) power series in free non-commuting variables, see for instance [8], [4] or a similar book on the subject. Our terminology, motivated by [3], differs however sometimes in the next section.

We denote by  $\mathcal{X}^*$  the free monoid on a set  $\mathcal{X} = \{X_1, \dots, X_k\}$ . We write 1 for the identity element and we use a boldface capital  $\mathbf{X}$  for a non-commutative monomial  $\mathbf{X} = X_{i_1}X_{i_2} \cdots X_{i_l} \in \mathcal{X}^*$ . We denote by

$$A = \sum_{\mathbf{X} \in \mathcal{X}^*} (A, \mathbf{X}) \mathbf{X} \in \mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle$$

a non-commutative formal power series where

$$\mathcal{X}^* \ni \mathbf{X} \longmapsto (A, \mathbf{X}) \in \mathbb{K}$$

stands for the coefficient function.

A formal power series  $A \in \mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle$  is invertible with respect to the obvious non-commutative product if and only if it has non-zero constant coefficient. We denote by  $\mathfrak{m} \subset \mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle$  the maximal ideal consisting of formal power series without constant coefficient and by  $\mathbb{K}^* + \mathfrak{m}$  the *unit-group* of the algebra  $\mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle$  which is thus the non-commutative multiplicative group consisting of all (multiplicatively) invertible elements in  $\mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle$ . The unit group is isomorphic to the direct product  $\mathbb{K}^* \times (1 + \mathfrak{m})$  where  $\mathbb{K}^*$  is the central subgroup consisting of non-zero constants and where  $1 + \mathfrak{m}$  denotes the multiplicative subgroup given by the affine subspace spanned by power series with constant coefficient 1. We have

$(1 - a)^{-1} = 1 + \sum_{n=1}^{\infty} a^n$  for the multiplicative inverse  $(1 - a)^{-1}$  of an element  $1 - a \in 1 + \mathfrak{m}$ .

## 6.1 The shuffle algebra

The *shuffle-product*  $\mathbf{X} \sqcup \mathbf{X}'$  of two non-commutative monomials  $\mathbf{X}, \mathbf{X}' \in \mathcal{X}^*$  of degrees  $a = \deg(\mathbf{X})$  and  $b = \deg(\mathbf{X}')$  (for the obvious grading given by  $\deg(X_1) = \dots = \deg(X_k) = 1$ ) is the sum of all  $\binom{a+b}{a}$  monomials of degree  $a + b$  obtained by “shuffling” in every possible way the linear factors (elements of  $\mathcal{X}$ ) involved in  $\mathbf{X}$  with the linear factors of  $\mathbf{X}'$ . Such a monomial contribution to  $\mathbf{X} \sqcup \mathbf{X}'$  can be thought of as a monomial of degree  $a + b$  whose linear factors are coloured by two colours with  $\mathbf{X}$  corresponding to the product of all linear factors of the first colour and  $\mathbf{X}'$  corresponding to the product of the remaining linear factors. The shuffle product  $\mathbf{X} \sqcup \mathbf{X}'$  can also be recursively defined by  $\mathbf{X} \sqcup 1 = 1 \sqcup \mathbf{X} = \mathbf{X}$  and

$$(\mathbf{X}X_s) \sqcup (\mathbf{X}'X_t) = (\mathbf{X} \sqcup (\mathbf{X}'X_t))X_s + ((\mathbf{X}X_s) \sqcup \mathbf{X}')X_t$$

where  $X_s, X_t \in \mathcal{X} = \{X_1, \dots, X_k\}$  are monomials of degree 1.

Extending the shuffle-product in the obvious way to formal power series endows the vector space  $\mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle$  with an associative and commutative algebra structure called the *shuffle-algebra* which has close connections with multiple zeta values, the algebra of quasi-symmetric functions etc, see eg. [6]. In the case of one variable  $X = X_1$  we recover the definition of Section 3.

The group  $\mathrm{GL}_k(\mathbb{K})$  acts on the vector-space  $\mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle$  by a linear change of variables. This action induces an automorphism of the multiplicative (non-commutative) algebra or of the (commutative) shuffle algebra underlying  $\mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle$ .

Identifying all variables  $X_j$  of a formal power series  $A \in \mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle$  with a common variable  $X$  yields a homomorphism of algebras (respectively shuffle-algebras) from  $\mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle$  into the commutative algebra (respectively into the shuffle-algebra)  $\mathbb{K}[[X]]$ .

The commutative unit group (set of invertible elements for the shuffle-product) of the shuffle algebra is given by the set  $\mathbb{K}^* + \mathfrak{m}$  and is isomorphic to the direct product  $\mathbb{K}^* \times (1 + \mathfrak{m})$ . The inverse of an element  $1 - a \in 1 + \mathfrak{m}$  is given by  $\sum_{n=0}^{\infty} a \sqcup^n = 1 + a + a \sqcup a + a \sqcup a \sqcup a + \dots$ , cf. Remark 3.2.

The following result generalises Proposition 3.3:

**Proposition 6.1.** *Over a field of positive characteristic  $p$ , the subgroup  $1 + \mathfrak{m}$  of the shuffle-group is an  $\mathbb{F}_p$ -vector space of infinite dimension.*

**Proof** Contributions to a  $p$ -fold shuffle product  $A_1 \sqcup A_2 \sqcup \dots \sqcup A_p$  are given by monomials with linear factors coloured by  $p$  colours  $\{1, \dots, p\}$



keeping track of their “origin” with coefficients given by the product of the corresponding “monochromatic” coefficients in  $A_1, \dots, A_p$ . A permutation of the colours  $\{1, \dots, p\}$  (and in particular, a cyclic permutation of all colours) leaves such a contribution invariant if  $A_1 = \dots = A_p$ . Forgetting the colours, coefficients of degree  $> 0$  in  $A \sqcup^p$  are thus zero in characteristic  $p$ .  $\square$

## 7 Rational formal power series

A formal power series  $A$  is *rational* if it belongs to the smallest subalgebra in  $\mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle$  which contains the free associative algebra  $\mathbb{K}\langle X_1, \dots, X_k \rangle$  of non-commutative polynomials and intersects the multiplicative unit group of  $\mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle$  in a subgroup.

The (generalised) *Hankel matrix*  $H = H(A)$  of

$$A = \sum_{\mathbf{X} \in \mathcal{X}^*} (A, \mathbf{X}) \mathbf{X} \in \mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle$$

is the infinite matrix with rows and columns indexed by the free monoid  $\mathcal{X}^*$  of monomials and entries  $H_{\mathbf{X}\mathbf{X}'} = (A, \mathbf{X}\mathbf{X}')$ . In analogy with the terminology of [3], we call the rank  $\text{rank}(H) \in \mathbb{N} \cup \{\infty\}$  the *complexity* of  $A$ . The row-span, denoted by  $\overline{A}$ , of  $H$  is the *recursive closure* of  $A$ . It corresponds to the syntactic ideal of [4] and its dimension  $\dim(\overline{A})$  is the complexity of  $A$ .

**Remark 7.1.** *In the case of one variable, the complexity  $\dim(\overline{A})$  of a non-zero rational fraction  $A = \frac{f}{g}$  with  $f \in \mathbb{K}[X]$  and  $g \in 1 + X\mathbb{K}[X]$  is given by  $\dim(\overline{A}) = \max(1 + \deg(f), \deg(g))$ .*

Rational series coincide with series of finite complexity by a Theorem of Schützenberger (cf. [4], Theorem 1 of page 22).

We call a subspace  $\mathcal{A} \subset \mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle$  *recursively closed* if it contains the recursive closure of all its elements.

Given a monomial  $\mathbf{T} \in \mathcal{X}^*$ , we denote by

$$\rho(\mathbf{T}) : \mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle \longrightarrow \mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle$$

the linear application which associates to  $A = \sum_{\mathbf{X} \in \mathcal{X}^*} (A, \mathbf{X}) \mathbf{X} \in \mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle$  the formal power series  $\rho(\mathbf{T})A = \sum_{\mathbf{X} \in \mathcal{X}^*} (A, \mathbf{X}\mathbf{T}) \mathbf{X}$ . We have  $\rho(\mathbf{T})\rho(\mathbf{T}') = \rho(\mathbf{T}\mathbf{T}')$ . It is easy to check that the set  $\{\rho(\mathbf{T})A\}_{\mathbf{T} \in \mathcal{X}^*}$  spans the recursive closure  $\overline{A}$  of a power series  $A$ .

**Theorem 7.2.** *We have the inclusion*

$$\overline{A \sqcup B} \subset \overline{A} \sqcup \overline{B}$$

*for the shuffle product  $A \sqcup B$  of  $A, B \in \mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle$ .*

**Corollary 7.3.** *We have*

$$\dim(\overline{A \sqcup B}) \leq \dim(\overline{A}) \dim(\overline{B})$$

for the shuffle product  $A \sqcup B$  of  $A, B \in \mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle$ .

In particular, shuffle products of rational elements in  $\mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle$  are rational.

**Proof of Theorem 7.2** The shuffle product  $A \sqcup B$  is clearly contained in the vector space

$$\overline{A} \sqcup \overline{B} = \{Y \sqcup Z \mid Y \in \overline{A}, Z \in \overline{B}\}.$$

For  $Y \in \overline{A}, Z \in \overline{B}$  and  $X_s \in \mathcal{X} = \{X_1, \dots, X_k\}$ , the recursive definition of the shuffle product given in Section 6.1 shows

$$\rho(X_s)(Y \sqcup Z) = (\rho(X_s)Y) \sqcup Z + Y \sqcup (\rho(X_s)Z) \in \overline{A} \sqcup Z + Y \sqcup \overline{B} \subset \overline{A} \sqcup \overline{B}$$

and the vector space  $\overline{A} \sqcup \overline{B}$  is thus recursively closed.  $\square$

**Remark 7.4.** *Similar arguments show that the set of rational series is also closed under the ordinary product (and multiplicative inversion of invertible series), Hadamard product and composition (where one considers  $A \circ (B_1, \dots, B_k)$  with  $A \in \mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle$  and  $B_1, \dots, B_k \in \mathfrak{m} \subset \mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle$ ).*

**Remark 7.5.** *The shuffle inverse of a rational element in  $\mathbb{K}^* + \mathfrak{m}$  is in general not rational in characteristic 0. An exception is given by geometric progressions  $\frac{1}{1 - \sum_{j=1}^k \lambda_j X_j} = \sum_{n=0}^{\infty} \left( \sum_{j=1}^k \lambda_j X_j \right)^n$  since we have*

$$\frac{1}{1 - \sum_{j=1}^k \lambda_j X_j} \sqcup \frac{1}{1 - \sum_{j=1}^k \mu_j X_j} = \frac{1}{1 - \sum_{j=1}^k (\lambda_j + \mu_j) X_j}.$$

(This identity corresponds to the equality  $e^{\lambda X} e^{\mu X} = e^{(\lambda + \mu)X}$  in the case of a unique variable  $X = X_1$ , see Remark 3.1.)

By Remark 3.10, there are no other such elements in  $1 + \mathfrak{m}$  in the case of a unique variable  $X = X_1$ . I ignore if the maximal rational shuffle subgroup of  $1 + \mathfrak{m} \subset \mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle$  (defined as the set of all rational elements in  $1 + \mathfrak{m}$  with rational inverse for the shuffle product) contains other elements if  $k \geq 2$  and if  $\mathbb{K}$  is a suitable field of characteristic 0.

**Remark 7.6.** *Any finite set of rational elements in  $\mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle$  over a field  $\mathbb{K}$  of positive characteristic is included in a unique minimal finite-dimensional recursively closed subspace of  $\mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle$  which intersects the shuffle group  $\mathbb{K}^* + \mathfrak{m}$  in a subgroup.*

## 8 The $p$ -homogeneous form $\sigma : \overline{\mathbb{F}_p} \langle\langle X_1, \dots, X_k \rangle\rangle \longrightarrow \overline{\mathbb{F}_p} \langle\langle X_1, \dots, X_k \rangle\rangle$

Considering an integral lift  $\tilde{A} = \tilde{\alpha} + \tilde{a} \in \overline{\mathbb{Q}} \langle\langle X_1, \dots, X_k \rangle\rangle$  with coefficients in algebraic integers of  $A = \alpha + a \in \alpha + \mathfrak{m} \subset \overline{\mathbb{F}_p} \langle\langle X_1, \dots, X_k \rangle\rangle$ , we define  $\sigma(A)$  by the reduction of  $\tilde{\alpha}^p + \tilde{b}$  modulo  $p$  where

$$\tilde{A} \sqcup^p = \tilde{\alpha}^p + p\tilde{b} \in \tilde{\alpha}^p + \mathfrak{m} \subset \overline{\mathbb{Q}} \langle\langle X_1, \dots, X_k \rangle\rangle .$$

This definition corresponds to the definition of  $\sigma$  given in Section 5 in the case of one variable  $X = X_1$ .

**Proposition 8.1.** *One has*

$$\dim(\overline{\sigma(A)}) \leq 1 + \binom{\dim(\overline{A}) + p - 1}{p}$$

for  $A \in \overline{\mathbb{F}_p} \langle\langle X_1, \dots, X_k \rangle\rangle$ .

*In particular,  $\sigma(A)$  is rational for rational  $A \in \overline{\mathbb{F}_p} \langle\langle X_1, \dots, X_k \rangle\rangle$ .*

**Proof** It is always possible to choose an integral lift  $\tilde{A} \in \overline{\mathbb{Q}} \langle\langle X_1, \dots, X_k \rangle\rangle$  of  $A \in \overline{\mathbb{F}_p} \langle\langle X_1, \dots, X_k \rangle\rangle$  such that  $\dim(\overline{\tilde{A}}) = \dim(\overline{A})$ . The inclusion

$$\overline{(\tilde{A} \sqcup^p)} \subset (\overline{\tilde{A}}) \sqcup^p$$

implies then easily the result.  $\square$

It is easy to show that  $\sigma$  induces a bijection on the subset  $1 + \mathfrak{m} \subset \mathbb{K} \langle\langle X_1, \dots, X_k \rangle\rangle$  for a field  $\mathbb{K} \subset \overline{\mathbb{F}_p}$ . Computations of a few examples in  $\mathbb{F}_2 \langle\langle X_1, X_2 \rangle\rangle$  suggest:

**Conjecture 8.2.** *The formal power series  $\sigma^{-1}(A)$  is rational for rational  $A \in 1 + \mathfrak{m} \subset \overline{\mathbb{F}_p} \langle\langle X_1, \dots, X_k \rangle\rangle$ .*

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