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Roland Bacher

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On exponentials of exponential generating series

Roland Bacher

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Abstract¹: Identifying the algebra of exponential generating series with the shuffle algebra of formal power series, one can define an exponential map $\exp_1 : X\mathbb{K}[[X]] \rightarrow 1 + X\mathbb{K}[[X]]$ for the associated Lie group formed by exponential generating series with constant coefficient 1 over an arbitrary field \mathbb{K} . The main result of this paper states that the associated exponential map \exp_1 (and its reciprocal map \log_1) induces a bijection between rational, respectively algebraic, series in $X\mathbb{K}[[X]]$ and $1 + X\mathbb{K}[[X]]$ if the field \mathbb{K} is a subfield of the algebraically closed field $\overline{\mathbb{F}}_p$ of characteristic p .

1 Introduction

The equality

$$\left(\sum_{n=0}^{\infty} \alpha_n \frac{X^n}{n!} \right) \left(\sum_{n=0}^{\infty} \beta_n \frac{X^n}{n!} \right) = \sum_{n=0}^{\infty} \sum_{m=0}^n \binom{n+m}{n} \alpha_n \beta_m \frac{X^{n+m}}{(n+m)!}$$

shows that we can define an algebra structure on the vector space

$$\mathcal{E}(\mathbb{K}) = \left\{ \sum_{n=0}^{\infty} \alpha_n \frac{X^n}{n!} \mid \alpha_0, \alpha_1, \dots \in \mathbb{K} \right\}$$

of exponential generating series with coefficients $\alpha_0, \alpha_1, \dots$ in an arbitrary field or ring \mathbb{K} . For the sake of simplicity we work in the sequel only over fields. The expression $\alpha_n/n!$ should be considered formally since the numerical value of $n!$ is zero over a field of positive characteristic $p \leq n$.

We denote by

$$\mathfrak{m}_{\mathcal{E}} = \left\{ \sum_{n=1}^{\infty} \alpha_n \frac{X^n}{n!} \mid \alpha_1, \alpha_2, \dots \in \mathbb{K} \right\} \subset \mathcal{E}(\mathbb{K})$$

the maximal ideal of the local algebra $\mathcal{E}(\mathbb{K})$. A straightforward computation shows that $a^n/n!$ is well-defined for $a \in \mathfrak{m}_{\mathcal{E}}$ over an arbitrary field.

¹Keywords: Bell numbers, exponential function, shuffle product, formal power series, rational series, algebraic series, homogeneous form, automaton sequence, Math. class: 11B73, 11B85, 11E08, 11E76, 22E65

Endowing \mathbb{K} with the discrete topology and $\mathcal{E}(\mathbb{K})$ with the topology given by coefficientwise convergency, the functions

$$\exp(a) = \sum_{n=0}^{\infty} \frac{a^n}{n!} \text{ and } \log(1+a) = - \sum_{n=1}^{\infty} \frac{(-a)^n}{n}$$

are always defined for $a \in \mathfrak{m}_{\mathcal{E}}$.

Switching back to ordinary generating series

$$A = \sum_{n=1}^{\infty} \alpha_n X^n, \quad B = \sum_{n=1}^{\infty} \beta_n X^n \in \mathfrak{m}$$

contained in the maximal ideal $\mathfrak{m} = X\mathbb{K}[[X]]$, of (ordinary) formal power series, we write

$$\exp_!(A) = 1 + B$$

if

$$\exp \left(\sum_{n=1}^{\infty} \alpha_n \frac{X^n}{n!} \right) = 1 + \sum_{n=1}^{\infty} \beta_n \frac{X^n}{n!} .$$

It is easy to see that $\exp_!$ defines a one-to-one map from \mathfrak{m} onto $1 + \mathfrak{m}$ with inverse map

$$1 + B \longmapsto A = \log_!(1 + B) .$$

It satisfies

$$\exp_!(A + B) = \exp_!(A) \sqcup \exp_!(B)$$

for all $A, B \in \mathfrak{m}$ where the shuffle product

$$\left(\sum_{n=0}^{\infty} \alpha_n X^n \right) \sqcup \left(\sum_{n=0}^{\infty} \beta_n X^n \right) = \sum_{n,m=0}^{\infty} \binom{n+m}{n} \alpha_n \beta_m X^{n+m}$$

corresponds to the ordinary product of the associated exponential generating series. The map $\exp_!$ defines thus an isomorphism from the additive group $(\mathfrak{m}, +)$ onto the *special shuffle-group* $(1 + \mathfrak{m}, \sqcup)$ with group-law given by the shuffle-product. It coincides with the familiar exponential map from the Lie algebra \mathfrak{m} into the special shuffle group, considered as an infinite-dimensional Lie group.

Theorem 1.1. *Let \mathbb{K} be a subfield of the algebraically closed field $\overline{\mathbb{F}}_p$ of positive characteristic p . Given a series $A \in \mathfrak{m} = X\mathbb{K}[[X]]$ the following two assertions are equivalent:*

- (i) *A is rational.*
- (ii) *$\exp_!(A)$ is rational.*

Example 1.2. The Bell numbers B_0, B_1, B_2, \dots , see pages 45,46 in [5] or Example 5.2.4 in [7], are the natural integers defined by

$$\sum_{n=0}^{\infty} B_n \frac{x^n}{n!} = e^{e^x - 1}$$

and have combinatorial interpretations.

Reducing the associated ordinary generating series $\sum_{n=0}^{\infty} B_n x^n = \exp_1(x/(1-x))$ modulo a prime p defines the series expansion of a rational fraction. A few reductions of the ordinary generating series

$$\sum_{n=0}^{\infty} B_n x^n = 1 + x + 2x^2 + 5x^3 + 15x^4 + 52x^5 + 203x^6 + 877x^7 + 4140x^8 + \dots$$

of Bell numbers modulo small primes are

$$\frac{1}{1+x+x^2} \pmod{2}, \quad \frac{1+x+x^2}{1-x^2-x^3} \pmod{3}, \quad \frac{1+x+2x^2-x^4}{1-x^4-x^5} \pmod{5}.$$

Theorem 1.3. Let \mathbb{K} be a subfield of the algebraically closed field $\overline{\mathbb{F}}_p$ of positive characteristic p . Given a series $A \in \mathfrak{m} = X\mathbb{K}[[X]]$ the following two assertions are equivalent:

- (i) A is algebraic.
- (ii) $\exp_1(A)$ is algebraic.

Corollary 1.4. Over a subfield $\mathbb{K} \subset \overline{\mathbb{F}}_p$, the group isomorphism

$$\exp_1 : (\mathfrak{m}, +) \longrightarrow (1 + \mathfrak{m}, \sqcup)$$

restricts to an isomorphism between the subgroups of rational elements in $(\mathfrak{m}, +)$ and in $(1 + \mathfrak{m}, \sqcup)$.

It restricts also to an isomorphism between the subgroups of algebraic elements in $(\mathfrak{m}, +)$ and in $(1 + \mathfrak{m}, \sqcup)$.

Theorem 1.1 and 1.3 can be made effective:

Given a rational series $A \in \mathbb{K}[[X]]$ represented by a reduced fraction f/g where f, g with $g \neq 0$ are two coprime polynomials of degree $\deg(f)$ and $\deg(g)$, we set $\|A\| = \max(1 + \deg(f), \deg(g))$.

Theorem 1.5. We have

$$\|\exp_1(A)\| \leq p^{q^{\|A\|}} \quad \text{and} \quad \|\log_1(1+A)\| \leq 1 + \|1+A\|^p$$

for a rational series A in $\mathfrak{m} \subset \overline{\mathbb{F}}_p[[X]]$ having all its coefficients in a finite subfield $\mathbb{F}_q \subset \overline{\mathbb{F}}_p$ containing $q = p^e$ elements.

Given a prime p and a formal power series $C = \sum_{n=0}^{\infty} \gamma_n X^n$ in $\mathbb{K}_p[[X]]$ with coefficients in a subfield \mathbb{K} of $\overline{\mathbb{F}}_p$, we define for $f \in \mathbb{N}$, $k \in \mathbb{N}$, $k < p^f$ the series

$$C_{k,f} = \sum_{n=0}^{\infty} \gamma_{k+np^f} X^n .$$

We denote by $\kappa(C)$ the dimension $\dim(\sum_{k,f} \mathbb{K}C_{k,f}) \in \mathbb{N} \cup \{\infty\}$ of the vector space spanned by all series of the form $C_{k,f}$.

Algebraic series in $\mathbb{K}[[X]]$ for \mathbb{K} a subfield of $\overline{\mathbb{F}}_p$ are characterised by a Theorem of Christol (see Theorem 12.2.5 in [1]) stating that a series C in $\overline{\mathbb{F}}_p[[X]]$ is algebraic if and only if $\kappa(C)$ is finite. We have $\kappa(A+B) \leq \kappa(A) + \kappa(B)$ and an algebraic series $A \in \overline{\mathbb{F}}_p[[X]]$ has a minimal polynomial of degree at most $p^{\kappa(A)}$ with respect to A .

Theorem 1.6. *We have*

$$\kappa(\exp_1(A)) \leq q^{\kappa(A)} p^{q^{\kappa(A)}} \text{ and } \kappa(\log_1(1+A)) \leq 1 + 4(\kappa(1+A))^p$$

for an algebraic series A in $\mathfrak{m} \subset \overline{\mathbb{F}}_p[[X]]$ having all its coefficients in a finite subfield $\mathbb{F}_q \subset \overline{\mathbb{F}}_p$ containing $q = p^e$ elements.

A map $\mu : \mathcal{V} \rightarrow \mathcal{W}$ between two \mathbb{K} -vector spaces is a homogeneous form of degree d if $l \circ \mu : \mathcal{V} \rightarrow \mathbb{K}$ is homogeneous of degree d for every linear form $l : \mathcal{W} \rightarrow \mathbb{K}$.

A useful ingredient for proving Theorems 1.1, 1.3 and their effective versions is the following characterisation of \log_1 :

Proposition 1.7. *Over a field $\mathbb{K} \subset \overline{\mathbb{F}}_p$, the application $\log_1 : 1 + \mathfrak{m} \rightarrow \mathfrak{m}$ extends to a homogeneous form of degree p from $\mathbb{K}[[X]]$ into \mathfrak{m} .*

Example 1.8. *In characteristic 2, we have*

$$\log_1 \left(\sum_{n=0}^{\infty} \alpha_n X^n \right) = \sum_{n=0}^{\infty} \alpha_{2n}^2 X^{2n+1} + \sum_{0 \leq i < j} \binom{i+j}{i} \alpha_i \alpha_j X^{i+j}$$

for $\sum_{n=0}^{\infty} \alpha_n X^n$ in $1 + X\overline{\mathbb{F}}_2[[X]]$.

Notice that Theorems 1.1 and 1.3 fail in characteristic zero: We have $\log_1(1-X) = -\sum_{n=1}^{\infty} (n-1)! X^n$ which is obviously transcendental.

Remark 1.9. *Defining f_1 as*

$$f_1 \left(\sum_{n=1}^{\infty} \alpha_n X^n \right) = \sum_{n=1}^{\infty} \beta_n X^n$$

if

$$f \left(\sum_{n=1}^{\infty} \alpha_n \frac{X^n}{n!} \right) = \sum_{n=1}^{\infty} \beta_n \frac{X^n}{n!}$$

Theorems 1.1, 1.3, 1.5 and 1.6 have analogues for the functions \sin_1 and \tan_1 (and their reciprocal functions \arcsin_1 and \arctan_1).

The rest of the paper has two parts. In a first part we recall a few definitions and well-known results and prove all results mentioned above.

In a second part, starting at Section 8, we generalise Theorems 1.1 and 1.5 to formal power series in several non-commuting variables.

2 Rational and algebraic elements in $\mathbb{K}[[X]]$

This section recalls a few well-known facts concerning rational and algebraic elements in the algebra $\mathbb{K}[[X]]$ of formal power series.

We denote by $\tau : \mathbb{K}[[X]] \rightarrow \mathbb{K}[[X]]$ the shift operator

$$\tau \left(\sum_{n=0}^{\infty} \alpha_n X^n \right) = \sum_{n=0}^{\infty} \alpha_{n+1} X^n$$

acting on formal power series. The following well-known result characterises rational series:

Proposition 2.1. *A formal power series $A = \sum_{n=0}^{\infty} \alpha_n X^n$ of $\mathbb{K}[[X]]$ is rational if and only if the series $A, \tau(A), \tau^2(A), \dots, \tau^k(A) = \sum_{n=0}^{\infty} \alpha_{n+k} X^n, \dots$ span a finite-dimensional vector-space in $\mathbb{K}[[X]]$.*

More precisely, the vector space spanned by $A, \tau(A), \tau^2(A), \dots, \tau^i(A), \dots$ has dimension $\|A\| = \max(1 + \deg(f), \deg(g))$ if f/g with $f, g \in \mathbb{K}[X]$ is a reduced expression of a rational series A .

The function $A \rightarrow \|A\|$ satisfies the inequality

$$\|A + B\| \leq \|A\| + \|B\|$$

for rational series A, B in $\mathbb{K}[[X]]$. As a particular case we have

$$\|A\| - 1 \leq \|1 + A\| \leq \|A\| + 1.$$

Given a prime p and a formal power series $C = \sum_{n=0}^{\infty} \gamma_n X^n$ in $\overline{\mathbb{F}}_p[[X]]$ we denote by $\kappa(C) \in \mathbb{N} \cup \{\infty\}$ the dimension of the “ p -kernel”

$$\mathcal{K}(C) = \sum_{f,k} \overline{\mathbb{F}}_p C_{k,f}$$

spanned by all series

$$C_{k,f} = \sum_{n=0}^{\infty} \gamma_{k+np^f} X^n$$

for $f \in \mathbb{N}$, $k \in \mathbb{N}$, $k < p^f$.

Algebraic series of $\mathbb{K}[[X]]$ for \mathbb{K} a subfield of the algebraic closure $\overline{\mathbb{F}}_p$ of finite prime characteristic p are characterised by the following Theorem of Christol (see [4] or Theorem 12.2.5 in [1]):

Theorem 2.2. *A formal power series $C = \sum_{n=0}^{\infty} \gamma_n X^n$ of $\overline{\mathbb{F}}_p[[X]]$ is algebraic if and only if $\kappa(C)$ is finite.*

We state without proof the following well-known consequence.

Corollary 2.3. *An algebraic series of $\overline{\mathbb{F}}_p[[X]]$ has all its coefficients in a finite subfield of $\overline{\mathbb{F}}_p$.*

Proposition 2.4. *Let $C = \sum_{n=0}^{\infty} \gamma_n X^n$ be an algebraic series with coefficients in a subfield $\mathbb{K} \subset \overline{\mathbb{F}}_p$.*

(i) *We have*

$$\mathcal{K}(\tau(C)) \subset \mathcal{K}(C) + \tau(\mathcal{K}(C))$$

which implies

$$\kappa(\tau(C)) \leq 2\kappa(C) .$$

(ii) *We have*

$$\mathcal{K}(C) \subset \mathbb{K} + \mathcal{K}(\tau(C)) + X\mathcal{K}(\tau(C))$$

which implies

$$\kappa(C) \leq 1 + 2\kappa(\tau(C)) .$$

Proof Assertion (i) follows from an iterated application of the easy computations

$$(\tau(C))_{k,1} = C_{k+1,1}$$

if $0 \leq k < p - 1$ and

$$(\tau(C))_{p-1,1} = \tau(C_{0,1}) .$$

The proof of assertion (ii) is similar. □

3 The shuffle algebra

This section recalls mostly well-known results concerning shuffle products of elements in the set $\mathbb{K}[[X]]$ of formal power series over a commutative field \mathbb{K} which is arbitrary unless specified otherwise.

The *shuffle product*

$$A \sqcup B = C = \sum_{n=0}^{\infty} \gamma_n X^n$$

of $A = \sum_{n=0}^{\infty} \alpha_n X^n$ and $B = \sum_{n=0}^{\infty} \beta_n X^n$ is defined by

$$\gamma_n = \sum_{k=0}^n \binom{n}{k} \alpha_k \beta_{n-k}$$

and corresponds to the usual product $ab = c$ of the associated exponential generating series

$$a = \sum_{n=0}^{\infty} \alpha_n \frac{X^n}{n!}, \quad b = \sum_{n=0}^{\infty} \beta_n \frac{X^n}{n!}, \quad c = \sum_{n=0}^{\infty} \gamma_n \frac{X^n}{n!}.$$

The *shuffle algebra* is the algebra $(\mathbb{K}[[X]], \sqcup)$ obtained by endowing the vector space $\mathbb{K}[[X]]$ of ordinary generating series with the shuffle product. By construction, the shuffle algebra is isomorphic to the algebra $\mathcal{E}(\mathbb{K})$ of exponential generating series. In characteristic zero, the trivial identity

$$\sum_{n=0}^{\infty} \alpha_n X^n = \sum_{n=0}^{\infty} (n! \alpha_n) \frac{X^n}{n!}$$

gives an isomorphism between the usual algebra $\mathbb{K}[[X]]$ of ordinary generating series and the shuffle algebra $(\mathbb{K}[[X]], \sqcup)$.

The identity $\left(\sum_{n \geq 0} \lambda^n X^n\right) \sqcup \left(\sum_{n \geq 0} \mu^n X^n\right) = \sum_{n \geq 0} (\lambda + \mu)^n X^n$, equivalent to $e^{\lambda X} e^{\mu X} = e^{(\lambda + \mu)X}$ implies that the convergency radius of the shuffle product of two complex series with strictly positive convergency radii ρ_1, ρ_2 is at least the harmonic mean $1 / \left(\frac{1}{\rho_1} + \frac{1}{\rho_2}\right)$ of ρ_1 and ρ_2 .

Proposition 3.1. *The shift operator $\tau(\sum_{n=0}^{\infty} \alpha_n X^n) = \sum_{n=0}^{\infty} \alpha_{n+1} X^n$ acts as a derivation on the shuffle algebra.*

Proof The map τ is clearly linear. The computation

$$\begin{aligned} \tau \left(\sum_{i,j \geq 0} \binom{i+j}{i} \alpha_i \beta_j X^{i+j} \right) &= \sum_{i,j \geq 0} \binom{i+j}{i} \alpha_i \beta_j X^{i+j-1} = \\ &= \sum_{i,j \geq 0} \left(\binom{i+j-1}{i-1} + \binom{i+j-1}{j-1} \right) \alpha_i \beta_j X^{i+j-1} \end{aligned}$$

shows that τ satisfies the Leibniz rule $\tau(A \sqcup B) = \tau(A) \sqcup B + A \sqcup \tau(B)$. \square

Proposition 3.1 is trivial in characteristic zero: the usual derivation d/dX acts obviously as the shift operator on the algebra $\mathcal{E}(\mathbb{K})$ of exponential generating series over a field of characteristic zero.

Proposition 3.2. *Shuffle products of rational power series are rational.*

More precisely, we have

$$\| A \sqcup B \| \leq \| A \| \| B \|$$

for two rational series A, B in $\mathbb{K}[[X]]$.

Proof Proposition 3.1 implies $\tau^n (A \sqcup B) = \sum_{k=0}^n \binom{n}{k} \tau^k(A) \sqcup \tau^{n-k}(B)$. The series $\tau^n (A \sqcup B)$ belongs thus to the vector space spanned by shuffle products with factors in the vector-spaces $\sum_{n \geq 0} \mathbb{K} \tau^n(A)$ and $\sum_{n \geq 0} \mathbb{K} \tau^n(B)$. This implies the inequality. Proposition 2.1 ends the proof. \square

Proposition 3.3. *Shuffle products of algebraic series in $\overline{\mathbb{F}}_p[[X]]$ are algebraic.*

More precisely, we have

$$\kappa(A \sqcup B) \leq \kappa(A) \kappa(B) .$$

Proof Denoting as in Section 2 by $C_{k,f}$ the series

$$C_{k,f} = \sum_{n=0}^{\infty} \gamma_{k+np^f} X^n$$

associated to a series $C = \sum_{n=0}^{\infty} \gamma_n X^n$ and by $\kappa(C)$ the dimension of the vector space $\mathcal{K}(C) = \sum_{k,f} \overline{\mathbb{F}}_p C_{k,f}$, Lucas's identity (see [6])

$$\binom{n}{k} \equiv \prod_{i \geq 0} \binom{\nu_i}{\kappa_i} \pmod{p}$$

for $n = \sum_{i \geq 0} \nu_i p^i$, $k = \sum_{i \geq 0} \kappa_i p^i$ with $\nu_i, \kappa_i \in \{0, \dots, p-1\}$ implies

$$(A \sqcup B)_{k,1} = \sum_{i=0}^k \binom{k}{i} A_{i,1} \sqcup B_{k-i,1}$$

for $k = 0, \dots, p-1$. Iteration of this formula shows that $(A \sqcup B)_{k,f}$ (for arbitrary $k, f \in \mathbb{N}$ such that $k < p^f$) belongs to the vector space spanned by shuffle products with factors in the vector spaces $\mathcal{K}(A)$ and $\mathcal{K}(B)$ of dimension $\kappa(A)$ and $\kappa(B)$.

Christol's Theorem (Theorem 2.2) ends the proof. \square

4 The special shuffle-group

We call the group of units of the shuffle algebra $(\mathbb{K}[[X]], \sqcup)$ the *shuffle-group*. Its elements are given by the set $\mathbb{K}^* + X\mathbb{K}[[X]]$ underlying the multiplicative unit group. The shuffle-group is the direct product of the unit group \mathbb{K}^* of \mathbb{K} with the *special shuffle-group* $(1 + X\mathbb{K}[[X]], \sqcup)$.

The inverse in the shuffle group of $1 - A \in (1 + X\mathbb{K}[[X]], \sqcup)$ 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 $n \geq 1$.

This shows in particular the identity $(1 - X) \sqcup (\sum_{n=0}^{\infty} n! X^n) = 1$. Invertible rational (analytical) power series have thus generally a transcendental (non-analytical) shuffle-inverse over the complex numbers.

Proposition 4.1. *The special shuffle-group $(1 + X\mathbb{K}[[X]], \sqcup)$ is isomorphic to an infinite-dimensional \mathbb{F}_p -vector-space if the field \mathbb{K} is of positive characteristic p .*

Proposition 4.1 shows that $(1 + X\mathbb{K}[[X]], \sqcup)$ is not isomorphic to the multiplicative group structure on $1 + X\mathbb{K}[[X]]$ if \mathbb{K} is of positive characteristic.

Proof of Proposition 4.1 Follows from the fact that \exp_1 is a group isomorphism between the \mathbb{F}_p -vector space \mathfrak{m} and the special shuffle group.

One can also give a direct proof by computing $A \sqcup^p$. □

Remark 4.2. *One can show that 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 $\lambda \in \mathbb{C}$. (Compute $A \sqcup B = 1$ using the decomposition into simple fractions of the rational series A, B .)*

5 The exponential and the logarithm for exponential generating functions

Proposition 5.1. *For all natural numbers $j, k \geq 1$, the set $\{1, \dots, jk\}$ can be partitioned in exactly*

$$\frac{(jk)!}{(j!)^k k!}$$

different ways into k unordered disjoint subsets of j elements.

In particular, the rational number $(jk)!/((j!)^k k!)$ is an integer for all natural numbers j, k such that $j \geq 1$.

Proof The multinomial coefficient $(jk)!/(j!)^k$ counts the number of ways of partitioning $\{1, \dots, jk\}$ into k disjoint ordered subset of j elements. Dividing by $k!$ removes the order on these k subsets.

This proves that the formula defines an integer for all $j, k \geq 1$ and integrality holds also obviously for $k = 0$ and $j \geq 1$. □

Proposition 5.2. *For any natural integer $k \in \mathbb{N}$, there exists polynomials $P_{k,n} \in \mathbb{N}[\alpha_1, \dots, \alpha_n]$ such that*

$$\frac{1}{k!} \left(\sum_{n=1}^{\infty} \alpha_n \frac{X^n}{n!} \right)^k = \sum_{n=0}^{\infty} P_{k,n}(\alpha_1, \alpha_2, \dots, \alpha_n) \frac{X^n}{n!} .$$

Proof The contribution of a monomial

$$\alpha_1^{j_1} \alpha_2^{j_2} \dots \alpha_s^{j_s} \frac{X^{\sum_{i=1}^s i j_i}}{(\sum_{i=1}^s i j_i)!}$$

with $j_1 + j_2 + \dots + j_s = k$ to $(1/k!) (\sum_{n=1}^{\infty} \alpha_n X^n / n!)^k$ is given by

$$\begin{aligned} & \frac{1}{k!} \frac{k!}{(j_1)!(j_2)! \dots (j_s)!} \frac{(\sum_{i=1}^s i j_i)!}{\prod_{i=1}^s (i!)^{j_i}} \\ &= \left(\prod_{i=1}^s \frac{(i j_i)!}{(i!)^{j_i} (j_i)!} \right) \frac{(\sum_{i=1}^s i j_i)!}{\prod_{i=1}^s (i j_i)!} \end{aligned}$$

and the last expression is a product of a natural integer by Proposition 5.1 and of a multinomial coefficient. It is thus a natural integer. \square

Corollary 5.3. For $a = \sum_{n=1}^{\infty} \alpha_n \frac{X^n}{n!}$ the formulae

$$\exp \left(\sum_{n=1}^{\infty} \alpha_n \frac{X^n}{n!} \right) = \sum_{k=0}^{\infty} \sum_{n=0}^{\infty} P_{k,n}(\alpha_1, \dots, \alpha_n) \frac{X^n}{n!}$$

and

$$\log \left(1 + \sum_{n=1}^{\infty} \alpha_n \frac{X^n}{n!} \right) = \sum_{k=1}^{\infty} \sum_{n=0}^{\infty} (-1)^{k+1} (k-1)! P_{k,n}(\alpha_1, \dots, \alpha_n) \frac{X^n}{n!}$$

define the exponential function and the logarithm of an exponential generating series in $a \in \mathfrak{m}_{\mathcal{E}}$ respectively $1 + a \in 1 + \mathfrak{m}_{\mathcal{E}}$ over an arbitrary field \mathbb{K} . These functions are one-to-one and mutually reciprocal.

6 The logarithm as a p -homogeneous form over $\overline{\mathbb{F}}_p[[x]]$

Given a fixed prime number p , Proposition 4.1 shows that there exists polynomials $P_{p,n} \in \mathbb{N}[\alpha_0, \dots, \alpha_n]$ for $n \geq 1$ such that

$$\left(\sum_{n=0}^{\infty} \alpha_n X^n \right)^{\sqcup p} = \alpha_0^p + p \sum_{n=1}^{\infty} P_{p,n}(\alpha_0, \dots, \alpha_n) X^n .$$

The polynomials $P_{p,n}$ are homogeneous of degree p with respect to the variables $\alpha_0, \dots, \alpha_n$ and we denote by

$$\mu_p \left(\sum_{n=0}^{\infty} \alpha_n X^n \right) = \sum_{n=1}^{\infty} P_{p,n}(\alpha_0, \dots, \alpha_n) X^n$$

the p -homogeneous form defined by the ordinary generating series of the polynomials $P_{p,1}, P_{p,2}, \dots$

Proposition 6.1. *The restriction of μ_p to $1 + \mathfrak{m} \subset \overline{\mathbb{F}}_p[[X]]$ coincides with the function \log_1 .*

Proof We have

$$\tau(\mu_p(1 + A)) = (1 + A) \sqcup^{p-1} \sqcup \tau(1 + A)$$

for A in \mathfrak{m} . This identity defines the restriction of the p -homogenous form μ_p to $1 + \mathfrak{m}$. The identity $(1 + A) \sqcup^{p-1} \sqcup (1 + A) = 1$ shows that the same equation

$$\tau(\log_1(1 + A)) = (1 + A) \sqcup^{p-1} \sqcup \tau(1 + A)$$

is also satisfied by the function \log_1 since τ corresponds to the differential operator d/dX of the associated exponential series and since the shuffle product corresponds to the ordinary product of exponential generating series.

Since both series $\mu_p(1 + A)$ and $\log_1(1 + A)$ are without constant term, the equality $\tau(\mu_p(1 + A)) = \tau(\log_1(1 + A))$ implies the equality $\mu_p(1 + A) = \log_1(1 + A)$. \square

7 Proofs

Proposition 7.1. *If A in $X\overline{\mathbb{F}}_p[[X]]$ is rational (respectively algebraic) then the formal power series $\log_1(1 + A)$ is rational (respectively algebraic).*

More precisely, we have

$$\| \log_1(1 + A) \| \leq 1 + \| 1 + A \|^p ,$$

respectively

$$\kappa(\log_1(1 + A)) \leq 1 + 4(\kappa(1 + A))^p ,$$

for rational, respectively algebraic, A in $X\overline{\mathbb{F}}_p[[X]]$.

Proposition 7.2. *If A in $X\overline{\mathbb{F}}_p[[X]]$ is rational (respectively algebraic) then $\exp_1(A)$ is rational (respectively algebraic).*

More precisely, denoting by $q = p^e$ the cardinality of a finite field $\mathbb{F}_q \subset \overline{\mathbb{F}}_p$ containing all coefficients of A we have

$$\| \exp_1(A) \| \leq p^{q^{\|A\|}}$$

respectively

$$\kappa(\exp_1(A)) \leq q^{\kappa(A)} p^{q^{\kappa(A)}}$$

for rational respectively algebraic A in \mathfrak{m} .

Theorems 1.1, 1.3, 1.5 and 1.6 are now simple reformulations of Propositions 7.1 and 7.2.

Proof of Proposition 7.1 We have

$$\tau(\log_!(1 + A)) = (1 + A) \sqcup^{p-1} \sqcup \tau(A) .$$

This shows

$$\| \tau(\log_!(1 + A)) \| \leq \| 1 + A \|^{p-1} \| \tau(A) \| \leq \| 1 + A \| ^p$$

and implies

$$\| \log_!(1 + A) \| \leq 1 + \| 1 + A \| ^p .$$

This settles the rational case.

For algebraic A we have similarly

$$\begin{aligned} \kappa(\tau(\log_!(1 + A))) &\leq (\kappa(1 + A))^{p-1} \kappa(\tau(A)) = (\kappa(1 + A))^{p-1} \kappa(\tau(1 + A)) \leq \\ &\leq (\kappa(1 + A))^{p-1} 2\kappa(1 + A) \leq 2(\kappa(1 + A))^p \end{aligned}$$

showing

$$\kappa(\log_!(1 + A)) \leq 1 + 2\kappa(\tau(\log_!(1 + A))) \leq 1 + 4(\kappa(1 + A))^p$$

and ending the proof. \square

Given a vector-space $\mathcal{V} \subset \mathbb{K}[[X]]$ containing \mathbb{K} , we denote by $\Gamma(\mathcal{V})$ the shuffle-subgroup generated by all elements of $\mathcal{V} \cap (1 + X\mathbb{K}[[X]])$.

Lemma 7.3. *Every element of a vector space $\mathcal{V} \subset \mathbb{K}[[X]]$ containing the constants \mathbb{K} can be written as a linear combination of elements in $\Gamma(\mathcal{V})$.*

Proof We have the identity

$$A = (1 - \epsilon(A) + A) + (\epsilon(A) - 1)$$

where $\epsilon(\sum_{n=0}^{\infty} \alpha_n X^n) = \alpha_0$ is the augmentation map and where $(1 - \epsilon(A) + A)$ and $(\epsilon(A) - 1)$ are both in $\mathbb{K}\Gamma(\mathcal{V})$ for $A \in \mathcal{V}$. \square

Proof of Proposition 7.2 for rational A Corollary 2.3 shows that we can work over a finite subfield $\mathbb{K} = \mathbb{F}_q$ of $\overline{\mathbb{F}_p}$ with $q = p^e$.

Given a rational series A in $\mathfrak{m} = X\mathbb{K}[[X]]$, we denote by Γ_A the shuffle-subgroup generated by all elements of the set

$$\left\{ \bigcup_{n=0}^{\infty} (\tau^n(A) + \mathbb{K}) \right\} \cap \{1 + X\mathbb{K}[[X]]\}.$$

The group Γ_A is an \mathbb{F}_p -vector space generated by at most $q^{\|A\|}$ elements. We denote by $\mathbb{K}[\Gamma_A]$ the subalgebra of dimension $\leq p^{q^{\|A\|}}$ in $\mathbb{K}[[X]]$ spanned by all elements of Γ_A . The identity

$$\tau(\exp_!(A)) = \exp_!(A) \sqcup \tau(A)$$

and the fact that the linear application τ is a derivation of $\mathbb{K}[[X]]$ show the inclusion

$$\tau^n(\exp_!(A)) \in \exp_!(A) \sqcup \mathbb{K}[\Gamma_A]$$

which ends the proof since the right-hand side is a \mathbb{K} -vector space of dimension at most $p^{q^{\|A\|}}$.

Proposition 7.4. *We have for every prime number p and for all natural integers j, k such that $j \geq 1$ the identity*

$$\frac{(jk)!}{(j!)^k k!} \equiv \frac{(pjk)!}{((pj)!)^k k!} \pmod{p}.$$

Proof The right-hand-side counts partitions of $\{1, \dots, pjk\}$ into k subsets of pj elements. Consider the action on such partitions obtained from the group generated by the jk cyclic permutations $(i, i + jk, i + 2jk, \dots, i + (p-1)jk)$ for $i = 1, \dots, jk$. Its fixpoints are in bijection with partitions of $\{1, \dots, jk\}$ into k subsets of j elements. \square

Corollary 7.5. *$\exp_!$ and $\log_!$ commute with the “Frobenius substitution”*

$$\varphi\left(\sum_{n=0}^{\infty} \alpha_n X^n\right) = \sum_{n=0}^{\infty} \alpha_n X^{pn}$$

for series in $X\overline{\mathbb{F}}_p[[X]]$, respectively in $1 + X\overline{\mathbb{F}}_p[[X]]$.

This implies

$$(\exp_!(A))_{0,f} = \exp_!(A_{0,f})$$

Lemma 7.6. *We have*

$$(B \sqcup C)_{0,1} = B_{0,1} \sqcup C_{0,1}$$

Proof Follows from the identity

$$\binom{pn}{k} \equiv 0 \pmod{p}$$

if $k \not\equiv 0 \pmod{p}$. \square

Proof of Proposition 7.2 for algebraic A We work again over a finite subfield $\mathbb{K} = \mathbb{F}_q \subset \overline{\mathbb{F}}_p$ containing all coefficients of A .

Let Γ_A denote the shuffle subgroup generated by all elements in

$$(\mathcal{K}(A) + \mathbb{K}) \cap (1 + X\mathbb{K}[[X]])$$

where $\mathcal{K}(A) = \sum_{k,f} \mathbb{K}A_{k,f}$. We denote by $\mathbb{K}[\Gamma_A] \subset (\mathbb{K}[[X]], \sqcup)$ the shuffle-subalgebra of dimension at most $p^{q^{\kappa(A)}}$ spanned by all elements of the group $\Gamma(A) \subset (1 + X\mathbb{K}[[X]], \sqcup)$.

Using the convention $A_{0,0} = A$, we have for $B \in \mathbb{K}[\Gamma(A)]$ and for k such that $0 \leq k < p$

$$\begin{aligned} (\exp_{\dagger}(A_{0,f}) \sqcup B)_{k,1} &= \left(\tau^k (\exp_{\dagger}(A_{0,f}) \sqcup B) \right)_{0,1} = \\ &= \left(\sum_{j=0}^k \binom{k}{j} \tau^j (\exp_{\dagger}(A_{0,f})) \sqcup \tau^{k-j}(B) \right)_{0,1} = \\ &= \sum_{j=0}^k \binom{k}{j} (\tau^j (\exp_{\dagger}(A_{0,f})))_{0,1} \sqcup B_{k-j,1} \end{aligned}$$

where the last equality is due to Lemma 7.6 (and to the equality $(\tau^k(C))_{0,1} = C_{k,1}$ for $0 \leq k < p$).

An iterated application of the identity $\tau(\exp_{\dagger}(A_{0,f})) = \exp_{\dagger}(A_{0,f}) \sqcup \tau(A_{0,f})$ implies

$$(\tau^j(\exp_{\dagger}(A_{0,f})))_{0,1} \in \exp_{\dagger}(A_{0,f+1}) \sqcup \mathbb{K}[\Gamma(A)]$$

and shows the inclusion

$$(\exp_{\dagger}(A))_{k,f} \in \exp_{\dagger}(A_{0,f}) \sqcup \mathbb{K}[\Gamma_A]$$

for all k such that $0 \leq k < p^f$ and for $(k, f) = (0, 0)$. Since the vector space $\sum_f \mathbb{K} \exp_{\dagger}(A_{0,f})$ is of dimension at most $q^{\kappa(A)}$ we have the inequality

$$\kappa(\exp_{\dagger}(A)) \leq q^{\kappa(A)} p^{q^{\kappa(A)}}.$$

This ends the proof. \square

8 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 [7], [3] or a similar book on the subject. We use however sometimes a different terminology, motivated by [2].

We denote by \mathcal{X}^* the free monoid on a finite 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.

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 $\mathbb{K}^* + \mathfrak{m} = \mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle \setminus \mathfrak{m}$ the unit-group of the algebra $\mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle$ 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 formed 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 $1 - A \in 1 + \mathfrak{m}$.

8.1 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 all possible ways the linear factors (elements of \mathcal{X}) involved in \mathbf{X} with the linear factors of \mathbf{X}' . A monomial involved in $\mathbf{X} \sqcup \mathbf{X}'$ 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*. 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 linear substitutions. This action induces an automorphism of the multiplicative (non-commutative) algebra-structure or of the (commutative) shuffle algebra-structure underlying the vector space $\mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle$.

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

The commutative unit group (set of invertible elements for the shuffle-product) of the shuffle algebra, given by the set $\mathbb{K}^* + \mathfrak{m}$, is isomorphic to the direct product $\mathbb{K}^* \times (1 + \mathfrak{m})$ where $1 + \mathfrak{m}$ is endowed with the shuffle product.

The inverse of an element $1 - A \in (1 + \mathfrak{m}, \sqcup)$ is given by $\sum_{n=0}^{\infty} A \sqcup^n = 1 + A + A \sqcup A + A \sqcup A \sqcup A + \dots$

The following result generalises Proposition 4.1:

Proposition 8.1. *Over a field of positive characteristic p , the subgroup $1 + \mathfrak{m}$ of the shuffle-group is an infinite-dimensional \mathbb{F}_p -vector space.*

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 strictly positive degree in $A \sqcup^p$ are thus zero in characteristic p . \square

As in the one variable case, one can prove that

$$\frac{1}{k!} A \sqcup^k$$

is defined over an arbitrary field \mathbb{K} for $A \in \mathfrak{m}$. Indeed, monomials contributing to $A \sqcup^k$ can be considered as colored by k colours and the $k!$ possible colour-permutations yield identical contributions.

For $A \in \mathfrak{m}$, we denote by

$$\exp_1(A) = \sum_{n=0}^{\infty} \frac{1}{n!} A \sqcup^n$$

the resulting exponential map from the Lie algebra \mathfrak{m} into the infinite-dimensional commutatif Lie group $(1 + \mathfrak{m}, \sqcup)$. As expected, its reciprocal function is defined by

$$\log_1(1 + A) = \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n} A \sqcup^n.$$

In the case of a field \mathbb{K} of positive characteristic p the function \log_1 is again given by the restriction to $1 + \mathfrak{m}$ of a p -homogeneous form μ_p .

The form μ_p has all its coefficients in \mathbb{N} and is defined by the equality

$$A \sqcup^p = (A, 1)^p + p\mu_p(A)$$

over an arbitrary field.

9 Rational 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.

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 defined by

$$\rho(\mathbf{T})A = \sum_{\mathbf{X} \in \mathcal{X}^*} (A, \mathbf{X}\mathbf{T})\mathbf{X}$$

for $A = \sum_{\mathbf{X} \in \mathcal{X}^*} (A, \mathbf{X})\mathbf{X}$ in $\mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle$. The identity $\rho(\mathbf{T})(\rho(\mathbf{T}')A) = \rho(\mathbf{T}\mathbf{T}')A$ shows that we have a representation

$$\rho : \mathcal{X}^* \longrightarrow \text{End}(\mathbb{K}\langle\langle \mathcal{X} \rangle\rangle)$$

of the free monoid \mathcal{X}^* on \mathcal{X} . The *recursive closure* \overline{A} of a power series A is the vector-space spanned by its orbit $\rho(\mathcal{X}^*)A$ under $\rho(\mathcal{X}^*)$. We call the dimension $\dim(\overline{A})$ of \overline{A} the *complexity* of A .

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.

Rational series coincide with series of finite complexity by a Theorem of Schützenberger (cf. [3], Theorem 1 of page 22).

Remark 9.1. *In the case of one variable, the complexity $\dim(\overline{A})$ of a reduced non-zero rational fraction $A = \frac{f}{g}$ with $f \in \mathbb{K}[X]$ and $g \in 1 + X\mathbb{K}[X]$ equals $\dim(\overline{A}) = \max(1 + \deg(f), \deg(g))$.*

Remark 9.2. *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 $H_{\mathbf{X}\mathbf{X}'} = (A, \mathbf{X}\mathbf{X}')$. The rank $\text{rank}(H)$ is given by the complexity $\dim(\overline{A})$ of A and \overline{A} corresponds to the row-span of H .*

Given subspaces \mathcal{A}, \mathcal{B} of $\mathbb{K}\langle\langle \mathcal{X} \rangle\rangle$, we denote by $\mathcal{A} \sqcup \mathcal{B}$ the vector space spanned by all products $A \sqcup B$ with $A \in \mathcal{A}$ and $B \in \mathcal{B}$.

Proposition 9.3. *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 9.4. *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 Proposition 9.3 For $Y \in \overline{A}, Z \in \overline{B}$ and X in $\{X_1, \dots, X_k\}$, the recursive definition of the shuffle product given in Section 8.1 shows

$$\rho(X)(Y \sqcup Z) = (\rho(X)Y) \sqcup Z + Y \sqcup (\rho(X)Z) .$$

We have thus the inclusions

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

which show that the vector space $\overline{A} \sqcup \overline{B}$ is recursively closed. Proposition 9.3 follows now from the inclusion $A \sqcup B \in \overline{A} \sqcup \overline{B}$. \square

Remark 9.5. *Similar arguments show that the set of rational elements in $\mathbb{K}\langle\langle X_1, \dots, X_k \rangle\rangle$ 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 9.6. *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*

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

corresponding to $e^{\lambda X} e^{\mu X} = e^{(\lambda + \mu)X}$ in the one-variable case.

There are no other such elements in $1 + \mathfrak{m} \subset \mathbb{K}[[X]]$, see Remark 4.2. I ignore if the maximal rational shuffle subgroup of $1 + \mathfrak{m} \subset \mathbb{C}\langle\langle X_1, \dots, X_k \rangle\rangle$ (defined as the set of all rational elements in $1 + \mathfrak{m}$ with rational inverse for the shuffle product) contains other elements if $k \geq 2$.

Remark 9.7. *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 $(\mathbb{K}^* + \mathfrak{m}, \sqcup)$ in a subgroup.*

10 Main result for generating series in non-commuting variables

Theorem 10.1. *Let \mathbb{K} be a subfield of $\overline{\mathbb{F}_p}$. Given a non-commutative formal power series $A \in \mathfrak{m} \subset \mathbb{K}\langle\langle \mathcal{X} \rangle\rangle$, the following two assertions are equivalent:*

- (i) *A is rational.*
- (ii) *$\exp_1(A)$ is rational.*

More precisely, we have for a rational series A in \mathfrak{m} the inequalities

$$\dim \left(\overline{\log_1(1 + A)} \right) \leq 1 + (\dim(\overline{1 + A}))^p$$

and

$$\dim \left(\overline{\exp_1(A)} \right) \leq p^{q^{\dim(\bar{A})}}$$

where $q = p^e$ is the cardinality of a finite field \mathbb{F}_q containing all coefficients of A .

Proof The identity

$$\log_1(1 + A) = \sum_{X \in \mathcal{X}} \left((1 + A) \sqcup^{p-1} \sqcup \rho(X)A \right) X$$

and Corollary 9.4 show

$$\dim \left(\overline{\log_1(1 + A)} \right) \leq 1 + (\dim(\bar{1} + A))^p .$$

For the opposite direction we denote by $\mathbb{K} = \mathbb{F}_q$ a finite subfield of $\bar{\mathbb{F}}_p$ containing all coefficients of A . We have

$$\overline{\exp_1(A)} \subset \exp_1(A) \sqcup \mathbb{K}[\Gamma(A)]$$

where $\mathbb{K}[\Gamma(A)]$ is the shuffle subalgebra of dimension $\leq p^{q^{\dim(\bar{A})}}$ spanned by all elements of the group Γ generated by all elements of the form

$$(\bar{A} + \mathbb{K}) \cap (1 + \mathfrak{m}) .$$

This implies the inequality

$$\dim \left(\overline{\exp_1(A)} \right) \leq p^{q^{\dim(\bar{A})}}$$

which ends the proof. \square

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Roland BACHER
INSTITUT FOURIER
Laboratoire de Mathématiques
UMR 5582 (UJF-CNRS)
BP 74
38402 St Martin d'Hères Cedex (France)
e-mail: Roland.Bacher@ujf-grenoble.fr