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# Mathematical renormalization in quantum electrodynamics via noncommutative generating series<sup>1</sup>

G.H.E. Duchamp<sup>5,2</sup>, V. Hoang Ngoc Minh<sup>1,2</sup>,  
Q.H. Ngô<sup>2</sup>, K. Penson<sup>3</sup>, P. Simonnet<sup>4</sup>.

<sup>1</sup>Université Lille II, 1, Place Déliot, 59024 Lille, France.

<sup>2</sup>LIPN - UMR 7030, CNRS, 93430 Villetaneuse, France.

<sup>3</sup>Université Paris VI - LPTMC, 4, Place Jussieu, 75252 Paris Cedex 05, France.

<sup>4</sup>Université de Corse, Avenue Jean Nicoli, BP 52, 20250 Corte, France.

<sup>5</sup>Université Paris XVIII, 93430 Villetaneuse, France.

## Abstract

In this work, we focus on the approach by noncommutative formal power series to study the combinatorial aspects of the renormalization at the singularities in  $\{0, 1, +\infty\}$  of the solutions of nonlinear differential equations involved in quantum electrodynamics.

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## 1 Introduction

During the last century, the functional expansions were common in physics as well as in engineering and have been developed, by Tomonaga, Schwinger and Feynman [16], to represent the nonlinear dynamical systems in quantum electrodynamics. The main difficulty of this approach is the divergence of these expansions at the singularity 0 or at  $+\infty$  (see [2]) and leads to the problems of *regularization* and *renormalization* which can be solved by combinatorial techniques : Feynman diagrams [18] and their derivatives [14, 23], noncommutative formal power series [19, 20], trees [10], . . . .

Recently, following the previous vein, and basing on

- the shuffle and quasi-shuffle Hopf algebras [5], the combinatorics on noncommutative formal power series were intensively amplified for the asymptotic analysis of nonlinear dynamical systems with three regular singularities in<sup>2</sup>  $\{0, 1, +\infty\}$  [39, 40],
- the monodromy and the Galois differential groups of the Knizhnik-Zamolodchikov differential equation  $KZ_3$  [38, 40], *i.e.* the following noncommutative evolution equation<sup>3</sup>

$$\frac{dG(z)}{dz} = \left( \frac{x_0}{z} + \frac{x_1}{1-z} \right) G(z), \quad (1)$$

the Schützenberger's monoidal factorization facilitates mainly the renormalization and the computation of the associators<sup>4</sup> via the universal one, *i.e.* the associator  $\Phi_{KZ}$  of Drinfel'd.

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<sup>2</sup>Any differential equation with three singularities in  $\{a, b, c\}$ , via homographic transformation  $(z-a)(c-b)(z-b)^{-1}(c-a)^{-1}$  can be changed into a differential equation with three singularities in  $\{0, 1, +\infty\}$ .

<sup>3</sup>Here,  $x_0$  and  $x_1$  are noncommutative variables. More precisely (with  $i^2 = -1$ ),

$$x_0 := \frac{t_{1,2}}{2i\pi} \quad \text{and} \quad x_1 := -\frac{t_{2,3}}{2i\pi},$$

where  $t_{1,2}$  and  $t_{2,3}$  belong to  $\mathcal{T}_3 = \{t_{1,2}, t_{1,3}, t_{2,3}\}$  satisfying the infinitesimal 3-braid relations

$$[t_{1,3}, t_{1,2} + t_{2,3}] = [t_{2,3}, t_{1,2} + t_{1,3}] = 0.$$

<sup>4</sup>They were introduced in quantum field theory by Drinfel'd and it plays an important role for the still open problem of the effective determination of the polynomial invariants of knots and links via Kontsevich's integral (see [6, 23]) and  $\Phi_{KZ}$ , was obtained firstly, in [23], with explicit coefficients which are polyzetas and regularized polyzetas (see [40, 41] for the computation of the other associators involving *only* convergent polyzetas as local coordinates, and for three algorithmical process to regularize the divergent polyzetas).

In fact, these associators are noncommutative formal power series on two variables and regularize the Chen generating series of the differential forms admitting singularities at 0 or at 1 along the integration paths on the universal covering  $\widehat{\mathbb{C} - \{0, 1\}}$  of  $\mathbb{C}$  without points 0 and 1. Their coefficients which are, up to multiple of power of  $2i\pi$ , polynomial on polyzetas, *i.e.* the following real numbers<sup>5</sup> (for  $r \geq 1, s_1 \geq 2$  and  $s_2, \dots, s_r \geq 1$ ) [42, 23, 51]

$$\zeta(s_1, \dots, s_r) = \sum_{n_1 > \dots > n_r > 0} \frac{1}{n_1^{s_1} \dots n_r^{s_r}} \quad (2)$$

and it is reasonable to think that these numbers admit a structure of  $\mathbb{N}$ -graded, by weight, algebra over the rational numbers deduced from the combinatorial aspects of the shuffle and quasi-shuffle Hopf algebras [40, 41].

More precisely, for  $s_1 \geq 2, s_2, \dots, s_r \geq 1$ , the polyzeta  $\zeta(s_1, \dots, s_r)$  can be obtained as the limit of

- the polylogarithm  $\text{Li}_{s_1, \dots, s_r}(z)$ , for  $z \rightarrow 1$  (recalled in Section 2.3.1)

$$\text{Li}_{s_1, \dots, s_r}(z) = \sum_{n_1 > \dots > n_r > 0} \frac{z^{n_1}}{n_1^{s_1} \dots n_r^{s_r}} \quad (3)$$

- the harmonic sum  $\text{H}_{s_1, \dots, s_r}(N)$ , for  $N \rightarrow +\infty$  (recalled in Section 2.3.1)

$$\text{H}_{s_1, \dots, s_r}(N) = \sum_{n_1 > \dots > n_r > 0}^N \frac{1}{n_1^{s_1} \dots n_r^{s_r}}. \quad (4)$$

Then, by a theorem of Abel, one has

$$\zeta(s_1, \dots, s_r) = \lim_{z \rightarrow 1} \text{Li}_{s_1, \dots, s_r}(z) = \lim_{N \rightarrow +\infty} \text{H}_{s_1, \dots, s_r}(N). \quad (5)$$

Since the algebras of polylogarithms and of harmonic sums are isomorphic respectively to the shuffle algebra  $(\mathbb{Q}\langle X \rangle, \sqcup)$  and the quasi-shuffle algebra  $(\mathbb{Q}\langle Y \rangle, \boxplus)$  both admitting the Lyndon words  $\mathcal{Lyn}X$  over  $X = \{x_0, x_1\}$  and  $\mathcal{Lyn}Y$  over  $Y = \{y_i\}_{i \geq 1}$ , as transcendence bases (recalled in Section 2.1) then, by using

- the correspondence between the composition in  $\mathbb{N}_+$  with the words in  $Y^*$  and in  $X^*x_1$ , *i.e.*

$$(s_1, \dots, s_r) \longleftrightarrow y_{s_1} \dots y_{s_r} \longleftrightarrow x_0^{s_1-1} x_1 \dots x_0^{s_r-1} x_1, \quad (6)$$

- the non commutative generating series in the factorized forms, *i.e.*

$$\text{L} = \prod_{l \in \mathcal{Lyn}X} \exp(\text{Li}_{S_l} P_l) \quad \text{and} \quad \text{H} = \prod_{l \in \mathcal{Lyn}Y} \exp(\text{H}_{\Sigma_l} \Pi_l), \quad (7)$$

$$\text{Z}_{\sqcup} = \prod_{\substack{l \in \mathcal{Lyn}X \\ l \neq x_0, x_1}} \exp(\zeta(S_l) P_l) \quad \text{and} \quad \text{Z}_{\boxplus} = \prod_{\substack{l \in \mathcal{Lyn}Y \\ l \neq y_1}} \exp(\zeta(\Sigma_l) \Pi_l), \quad (8)$$

---

<sup>5</sup>The sum  $s_1 + \dots + s_r$  is the *weight* of  $\zeta(s_1, \dots, s_r)$  which equals to the weight of the composition  $(s_1, \dots, s_r)$ .

where  $\{S_l\}_{l \in \mathcal{L}_{ynX}}$  and  $\{\Sigma_l\}_{l \in \mathcal{L}_{ynY}}$  are transcendence bases of  $(\mathbb{Q}\langle X \rangle, \sqcup)$  and  $(\mathbb{Q}\langle Y \rangle, \sqcup)$ ,  $\{P_l\}_{l \in \mathcal{L}_{ynX}}$  and  $\{\Pi_l\}_{l \in \mathcal{L}_{ynY}}$  are bases of the Lie algebras of the primitive elements of the bi-algebras  $\mathcal{H}_{\sqcup} = (\mathbb{Q}\langle X \rangle, \text{conc}, \Delta_{\sqcup}, 1_{X^*})$  and  $\mathcal{H}_{\sqcup} = (\mathbb{Q}\langle Y \rangle, \text{conc}, \Delta_{\sqcup}, 1_{Y^*})$  in duality respectively with  $\{S_l\}_{l \in \mathcal{L}_{ynX}}$  and  $\{\Sigma_l\}_{l \in \mathcal{L}_{ynY}}$ ,

we obtain the Abel like theorem [39, 40, 41], *i.e.* there exist two noncommutative formal series over  $Y$ ,  $Z_1$  and  $Z_2$  with constant terms, such that :

$$\lim_{z \rightarrow 1} \exp\left(y_1 \log \frac{1}{1-z}\right) \pi_Y L(z) = Z_1, \quad (9)$$

$$\lim_{N \rightarrow \infty} \exp\left(\sum_{k \geq 1} H_{y_k}(N) \frac{(-y_1)^k}{k}\right) H(N) = Z_2. \quad (10)$$

Moreover,  $Z_1, Z_2$  are equal and stand for the noncommutative generating series of the convergent polyzetas  $\{\zeta(w)\}_{w \in Y^* - y_1 Y^*}$ , or equivalently  $\{\zeta(w)\}_{w \in x_0 X^* x_1}$  :

$$Z_1 = Z_2 = \pi_Y Z_{\sqcup}, \quad (11)$$

where  $\pi_Y$  denotes the projection over  $Y^*$ .

This Abel theorem allows to explicit the counter-terms eliminating the divergence of

- the polylogarithms  $\{Li_w(z)\}_{w \in x_1 X^*}$  for  $z \rightarrow 1$ ,
- the harmonic sums  $\{H_w(N)\}_{w \in y_1 Y^*}$  for  $N \rightarrow \infty$

and leads naturally to an equation connecting these two algebraic structures

$$\prod_{\substack{l \in \mathcal{L}_{ynY} \\ l \neq y_1}} \exp(\zeta(\Sigma_l) \Pi_l) = \exp\left(\sum_{k \geq 2} \zeta(k) \frac{(-y_1)^k}{k}\right) \pi_Y \prod_{\substack{l \in \mathcal{L}_{ynX} \\ l \neq x_0, x_1}} \exp(\zeta(S_l) P_l). \quad (12)$$

This identity (12) enables, in particular,

- to calculate the Euler-Mac Laurin constants and the Hadamard finite parties associated to the divergent polyzetas  $\{\zeta(w)\}_{w \in y_1 Y^*}$ ,
- to describe *completely*, via identification of local coordinates in infinite dimension, the kernel of  $\zeta$  by its *algebraic* generators, and thus this kernel is generated by homogenous polynomials.

In this paper, we will focus on the approach by noncommutative formal power series, adapted from [19, 20], and explaining the results of [39, 40, 41] allowing to study the combinatorial aspects of the renormalization at the singularities in  $\{0, 1, +\infty\}$  of the solutions of linear differential equations (see Example 1 bellow) as well as the solutions of nonlinear differential equations (see Examples 2 and 3 bellow) described in Section 3.2 and involved in quantum electrodynamics.

**Example 1** (Hypergeometric equation). Let  $t_0, t_1, t_2$  be parameters and

$$z(1-z)\ddot{y}(z) + [t_2 - (t_0 + t_1 + 1)z]\dot{y}(z) - t_0t_1y(z) = 0.$$

Let  $q_1(z) = y(z)$  and  $q_2(z) = z(1-z)\dot{y}(z)$ . One has

$$\begin{pmatrix} \dot{q}_1 \\ \dot{q}_2 \end{pmatrix} = \begin{pmatrix} M_0 & M_1 \\ z & 1-z \end{pmatrix} \begin{pmatrix} q_1 \\ q_2 \end{pmatrix},$$

where  $M_0$  and  $M_1$  are the following matrices

$$M_0 = -\begin{pmatrix} 0 & 0 \\ t_0t_1 & t_2 \end{pmatrix} \quad \text{and} \quad M_1 = -\begin{pmatrix} 0 & 1 \\ 0 & t_2 - t_0 - t_1 \end{pmatrix}.$$

Or equivalently,

$$\begin{aligned} \dot{q}(z) &= A_0(q)\frac{1}{z} + A_1(q)\frac{1}{1-z}, \\ y(z) &= q(z), \end{aligned}$$

where  $A_0$  and  $A_1$  are the following parameterized linear vector fields

$$A_0(q) = -(t_0t_1q_1 + t_2q_2)\frac{\partial}{\partial q_2} \quad \text{and} \quad A_1(q) = -q_1\frac{\partial}{\partial q_1} - (t_2 - t_0 - t_1)q_2\frac{\partial}{\partial q_2}.$$

**Example 2** (Harmonic oscillator). Let  $k_1, k_2$  be parameters and

$$\ddot{y}(z) + k_1y(z) + k_2y^2(z) = u_1(z).$$

which can be represented by the following state equations

$$\begin{aligned} \dot{q}(z) &= A_0(q) + A_1(q)u_1(z), \\ y(z) &= q(z), \end{aligned}$$

where  $A_0$  and  $A_1$  are the following vector fields

$$A_0(q) = -(k_1q + k_2q^2)\frac{\partial}{\partial q} \quad \text{and} \quad A_1(q) = \frac{\partial}{\partial q}.$$

**Example 3** (Duffing's equation). Let  $a, b, c$  be parameters and

$$\ddot{y}(z) + ay(z) + by(z) + cy^3(z) = u_1(z).$$

which can be represented by the following state equations

$$\begin{aligned} \dot{q}(z) &= A_0(q) + A_1(q)u_1(z), \\ y(z) &= q(z), \end{aligned}$$

where  $A_0$  and  $A_1$  are the following vector fields

$$A_0(q) = -(aq_2 + b^2q_1 + cq_1^3)\frac{\partial}{\partial q_2} + q_2\frac{\partial}{\partial q_1} \quad \text{and} \quad A_1(q) = \frac{\partial}{\partial q_2}.$$

This approach by noncommutative formal power series is adequate for studying the algebraic combinatorial aspects of the asymptotic analysis, at the singularities in  $\{0, 1, +\infty\}$ , of the nonlinear dynamical systems described in Section 3.2 because

- the polylogarithms form the universal Picard-Vessiot of these nonlinear differential equations [38] and their algebra is isomorphic to the shuffle algebra admitting  $\{\text{Li}_l\}_{l \in \mathcal{L}yn X}$  as transcendence basis,
- the harmonic sums generate the coefficients of the ordinary Taylor expansion of their solutions (when these expansion exist) [39] and their algebra is isomorphic to the shuffle algebra admitting  $\{\text{H}_l\}_{l \in \mathcal{L}yn Y}$  as transcendence basis,
- the polyzetas do appear as the fundamental arithmetical constants involved in the computations of the monodromies [35, 32], the Kummer type functional equations [36, 32], the asymptotic expansions of the solutions of these equations [39, 40] and their algebra is freely generated by the polyzetas encoded by irreducible Lyndon words [40].

Hence, a lot of algorithms can be deduced from these facts and the more general studies will be proceed (see [5, 11] for example).

The organisation of this paper is following

- In Section 2, we will give algebraic and analytic foundations, *i.e.* the combinatorial Hopf algebra of shuffles and the indiscernability respectively, for polylogarithms and harmonic sums.
- These will be exploited systematically, in Section 3, to expand the solutions of nonlinear dynamical systems with singular inputs.

## 2 Background

### 2.1 Combinatorics on shuffle and stuffle Hopf algebras

#### 2.1.1 Schützenberger's monoidal factorization

Let  $X$  be a finite totally ordered alphabet. The free monoid and the set of Lyndon words, over  $X$ , are denoted respectively by  $X^*$  and  $\mathcal{L}yn X$ . The neutral element of  $X^*$  is denoted by  $1_{X^*}$ . Let  $\mathbb{Q}\langle X \rangle$  be equipped by the concatenation and the shuffle defined by

$$\forall w \in X^*, \quad w \sqcup 1_{X^*} = 1_{X^*} \sqcup w = w, \quad (13)$$

$$\forall x, y \in X, \forall u, v \in X^*, \quad xu \sqcup yv = x(u \sqcup yv) + y(xu \sqcup v), \quad (14)$$

or by their dual co-products,  $\Delta_{\text{conc}}, \Delta_{\sqcup}$ , defined by

$$\forall w \in X^*, \quad \Delta_{\text{conc}}(w) = \sum_{u, v \in X^*, uv=w} u \otimes v, \quad (15)$$

$$\forall x \in X, \quad \Delta_{\sqcup}(x) = x \otimes 1 + 1 \otimes x, \quad (16)$$

satisfying, for any  $u, v, w \in X^*$ ,

$$\langle \Delta_{\text{conc}}(w) \mid u \otimes v \rangle = \langle w \mid uv \rangle, \quad (17)$$

$$\langle \Delta_{\sqcup}(w) \mid u \otimes v \rangle = \langle w \mid u \sqcup v \rangle. \quad (18)$$

With the co-unit and the antipode defined by

$$\forall P \in \mathbb{Q}\langle X \rangle, \quad \epsilon(P) = \langle P \mid 1_{X^*} \rangle, \quad (19)$$

$$\forall w = x_{i_1} \dots x_{i_r} \in X^*, \quad a_{\sqcup}(w) = (-1)^{-|w|} x_{i_r} \dots x_{i_1}, \quad (20)$$

one gets two mutually dual Hopf algebras

$$\mathcal{H}_{\sqcup} = (\mathbb{Q}\langle X \rangle, \text{conc}, 1_{X^*}, \Delta_{\sqcup}, \epsilon, a_{\sqcup}), \quad (21)$$

$$\mathcal{H}_{\sqcup}^{\vee} = (\mathbb{Q}\langle X \rangle, \sqcup, 1_{X^*}, \Delta_{\text{conc}}, \epsilon, a_{\sqcup}). \quad (22)$$

By the Cartier-Quillen-Milnor-Moore theorem, the connected graded positively, co-commutative Hopf algebra  $\mathcal{H}$  is isomorphic to the envelopping algebra of the Lie algebra of its primitive elements which is equal to  $\mathcal{L}ie_{\mathbb{Q}}\langle X \rangle$ . Hence, any graded<sup>6</sup> suited<sup>7</sup> basis of  $\mathcal{L}ie_{\mathbb{Q}}\langle X \rangle$ , can be completed, by the Poincaré-Birkhoff-Witt theorem, as a linear (graded) basis  $\{b_w\}_{w \in X^*}$  for  $\mathcal{U}(\mathcal{L}ie_{\mathbb{Q}}\langle X \rangle)$ . One can then<sup>8</sup> construct, by duality, a basis  $\{\check{b}_w\}_{w \in X^*}$  of  $\mathcal{H}_{\sqcup}$  such that :

$$\forall u, v \in X^*, \quad \langle \check{b}_u \mid b_v \rangle = \delta_{u,v}, \quad (23)$$

and, for any  $x \in X$ ,  $\check{b}_x = x$  and for any  $w = l_1^{i_1} \dots l_k^{i_k}$  with  $l_1, \dots, l_k \in \mathcal{L}ynX$  and  $l_1 > \dots > l_k$ , one has

$$\check{b}_w = \frac{\check{b}_{l_1}^{i_1} \times \dots \times \check{b}_{l_k}^{i_k}}{i_1! \dots i_k!}. \quad (24)$$

For that, one can use a theorem of Viennot [50] to construct, by bijection with  $\mathcal{L}ynX$ , a basis for  $\mathcal{L}ie_{\mathbb{Q}}\langle X \rangle$  and, by the PBW theorem, one completes then to a linear basis for  $\mathcal{U}(\mathcal{L}ie_{\mathbb{Q}}\langle X \rangle)$ .

On an other way, by a Radford's theorem [45], the elements of  $\mathcal{L}ynX$  constitute also a transcendence basis for  $(\mathbb{Q}\langle X \rangle, \sqcup)$  and it can be completed then to the linear basis  $\{w\}_{w \in X^*}$  which is auto-dual :

$$\forall v, v \in X^*, \quad \langle u \mid v \rangle = \delta_{u,v}. \quad (25)$$

But the elements  $l \in \mathcal{L}ynX - X$  are not primitive, for  $\Delta_{\sqcup}$ , and then  $\mathcal{L}ynX$  does not constitute a basis for  $\mathcal{L}ie_{\mathbb{Q}}\langle X \rangle$ . Denoting  $\mathcal{D}_X$  the diagonal series over  $X$ , one has

$$\mathcal{D}_X = \sum_{w \in X^*} w \otimes w = \sum_{l \in \mathcal{L}ynX} l \otimes l + \sum_{w \notin \mathcal{L}ynX} w \otimes w \quad (26)$$

<sup>6</sup>for the multidegree.

<sup>7</sup>i.e. a basis of polynomials indexed by their initial words which is a Lyndon word.

<sup>8</sup>because  $\mathcal{H}$  is graded in finite dimensions by the multidegree.



and  $\mathcal{D}_X$  can be also factorized as follows

$$\mathcal{D}_X = \prod_{l \in \mathcal{L}yn X} \exp(l \otimes l). \quad (27)$$

Using the transcendence basis  $\{l\}_{l \in \mathcal{L}yn X}$ , Mélançon and Reutenauer give an other completion by putting [47]

$$S'_l = l, \quad \text{for } l \in \mathcal{L}yn X, \quad (28)$$

$$S'_w = \frac{l_1^{\sqcup i_1} \sqcup \dots \sqcup l_k^{\sqcup i_k}}{i_1! \dots i_k!}, \quad \text{for } w = l_1^{i_1} \dots l_k^{i_k}, l_1 > \dots > l_k, \quad (29)$$

$$= w + \sum_{v < w, |v|=|w|} c'_v v. \quad (30)$$

The linear basis  $\{S'_w\}_{w \in X^*}$  admits the dual basis  $\{P'_w\}_{w \in X^*}$  but it is not of PBW type although the elements of  $\{P'_l\}_{l \in \mathcal{L}yn X}$  are primitive, for  $\Delta_{\sqcup}$  [12].

Chen, Fox and Lyndon [8] constructed  $\{P_w\}_{w \in X^*}$ , so-called the PBW-Lyndon basis, for  $\mathcal{U}(\mathcal{L}ie_{\mathbb{Q}}\langle X \rangle)$  as follows

$$P_x = x \quad \text{for } x \in X, \quad (31)$$

$$P_l = [P_s, P_r] \quad \text{for } l \in \mathcal{L}yn X, \text{ standard factorization of } l = (s, r), \quad (32)$$

$$P_w = P_{l_1}^{i_1} \dots P_{l_k}^{i_k} \quad \text{for } w = l_1^{i_1} \dots l_k^{i_k}, l_1 > \dots > l_k, l_1, \dots, l_k \in \mathcal{L}yn X. \quad (33)$$

Schützenberger constructed bases for  $(\mathbb{Q}\langle X \rangle, \sqcup)$  defined by duality as follows :

$$\forall u, v \in X^*, \quad \langle S_u | P_v \rangle = \delta_{u,v}, \quad (34)$$

and obtained the transcendence basis  $\{S_l\}_{l \in \mathcal{L}yn X}$  and the linear basis  $\{S_w\}_{w \in X^*}$  as follows

$$S_l = x S_u, \quad \text{for } l = xu \in \mathcal{L}yn X, \quad (35)$$

$$S_w = \frac{S_{l_1}^{\sqcup i_1} \sqcup \dots \sqcup S_{l_k}^{\sqcup i_k}}{i_1! \dots i_k!} \quad \text{for } w = l_1^{i_1} \dots l_k^{i_k}, l_1 > \dots > l_k. \quad (36)$$

After that, Mélançon and Reutenauer [47] proved that<sup>9</sup>, for any  $w \in X^*$ ,

$$P_w = w + \sum_{v > w, |v|=|w|} c_v v \quad \text{and} \quad S_w = w + \sum_{v < w, |v|=|w|} c_v v. \quad (37)$$

<sup>9</sup> Recall that the duality preserves the (multi)-homogeneous degree and interchanges the triangularity of polynomials [47]. For that, one can construct the triangular matrices  $M$  and  $N$  admitting coefficients as the coefficients of the homogeneous of degree  $k$  triangular polynomials,  $\{P_w\}_{w \in X^*}$  and  $\{S_w\}_{w \in X^*}$  in the basis  $\{w\}_{w \in X^*}$  respectively :

$$M_{u,v} = \langle P_u | v \rangle \quad \text{and} \quad N_{v,u} = \langle S_u | v \rangle.$$

The triangular matrices  $M$  and  $N$  are unipotent and satisfy the identity  $N = ({}^t M)^{-1}$ .

In other words, the elements of the bases  $\{S_w\}_{w \in X^*}$  and  $\{P_w\}_{w \in X^*}$  are lower and upper triangular respectively and they are of homogeneous by degree.

Thanks to the duality of the bases  $\{P_w\}_{w \in X^*}$  and  $\{S_w\}_{w \in X^*}$  and the basis  $\{P_w\}_{w \in X^*}$  is of PBW type, one also has [47]

$$\mathcal{D}_X = \sum_{w \in X^*} S_w \otimes P_w \quad (38)$$

$$= \sum_{l \in \mathcal{Lyn}X} S_l \otimes P_l + \sum_{w \notin \mathcal{Lyn}X} S_w \otimes P_w \quad (39)$$

$$= \prod_{l \in \mathcal{Lyn}X} \exp(S_l \otimes P_l). \quad (40)$$

**Example 4** ([27]). Let  $X = \{x_0, x_1\}$  with  $x_0 < x_1$ .

$l$	$P_l$	$S_l$
$x_0$	$x_0$	$x_0$
$x_1$	$x_1$	$x_1$
$x_0x_1$	$[x_0, x_1]$	$x_0x_1$
$x_0^2x_1$	$[x_0, [x_0, x_1]]$	$x_0^2x_1$
$x_0x_1^2$	$[[x_0, x_1], x_1]$	$x_0x_1^2$
$x_0^3x_1$	$[x_0, [x_0, [x_0, x_1]]]$	$x_0^3x_1$
$x_0^2x_1^2$	$[x_0, [[x_0, x_1], x_1]]$	$x_0^2x_1^2$
$x_0x_1^3$	$[[[x_0, x_1], x_1], x_1]$	$x_0x_1^3$
$x_0^4x_1$	$[x_0, [x_0, [x_0, [x_0, x_1]]]]$	$x_0^4x_1$
$x_0^3x_1^2$	$[x_0, [x_0, [[x_0, x_1], x_1]]]$	$x_0^3x_1^2$
$x_0^2x_1x_0x_1$	$[[x_0, [x_0, x_1]], [x_0, x_1]]$	$2x_0^3x_1^2 + x_0^2x_1x_0x_1$
$x_0^2x_1^3$	$[x_0, [[[x_0, x_1], x_1], x_1]]$	$x_0^2x_1^3$
$x_0x_1x_0x_1^2$	$[[x_0, x_1], [[x_0, x_1], x_1]]$	$3x_0^2x_1^3 + x_0x_1x_0x_1^2$
$x_0x_1^4$	$[[[[x_0, x_1], x_1], x_1], x_1]$	$x_0x_1^4$
$x_0^5x_1$	$[x_0, [x_0, [x_0, [x_0, [x_0, x_1]]]]]$	$x_0^5x_1$
$x_0^4x_1^2$	$[x_0, [x_0, [x_0, [[x_0, x_1], x_1]]]]$	$x_0^4x_1^2$
$x_0^3x_1x_0x_1$	$[x_0, [[x_0, [x_0, x_1]], [x_0, x_1]]]$	$2x_0^4x_1^2 + x_0^3x_1x_0x_1$
$x_0^3x_1^3$	$[x_0, [x_0, [[[x_0, x_1], x_1], x_1]]]$	$x_0^3x_1^3$
$x_0^2x_1x_0x_1^2$	$[x_0, [[x_0, x_1], [[x_0, x_1], x_1]]]$	$3x_0^3x_1^3 + x_0^2x_1x_0x_1^2$
$x_0^2x_1^2x_0x_1$	$[[x_0, [[x_0, x_1], x_1]], [x_0, x_1]]$	$6x_0^3x_1^3 + 3x_0^2x_1x_0x_1^2 + x_0^2x_1^2x_0x_1$
$x_0^2x_1^4$	$[x_0, [[[[x_0, x_1], x_1], x_1], x_1]]]$	$x_0^2x_1^4$
$x_0x_1x_0x_1^3$	$[[x_0, x_1], [[[x_0, x_1], x_1], x_1]]]$	$4x_0^2x_1^4 + x_0x_1x_0x_1^3$
$x_0x_1^5$	$[[[[[[x_0, x_1], x_1], x_1], x_1], x_1]]]$	$x_0x_1^5$

### 2.1.2 Extended Schützenberger's monoidal factorization

Now, let  $Y = \{y_i\}_{i \geq 1}$  be an infinite totally ordered alphabet<sup>10</sup>. The free monoid and the set of Lyndon words, over  $Y$ , are denoted respectively by  $Y^*$  and  $\mathcal{Lyn}Y$ . The neutral element of  $Y^*$  is denoted by  $1_{Y^*}$ .

<sup>10</sup>by  $y_1 > y_2 > y_3 > \dots$

Let  $u = y_{i_1} \dots y_{i_k} \in Y^*$ , the *length* and the *weight* of  $u$  are defined respectively as the numbers  $|u| = k$  and  $(u) = i_1 + \dots + i_k$ .

Let us define the commutative product over  $\mathbb{Q}\langle Y \rangle$ , denoted by  $\mu$ , as follows

$$\forall y_n, y_m \in Y, \quad \mu(y_n, y_m) = y_{n+m}, \quad (41)$$

or by its associated coproduct,  $\Delta_+$ , defined by

$$\forall y_n \in Y, \quad \Delta_+ y_n = \sum_{i=1}^{n-1} y_i \otimes y_{n-i} \quad (42)$$

satisfying,

$$\forall x, y, z \in Y, \quad \langle \Delta_+ x \mid y \otimes z \rangle = \langle x \mid \mu(y, z) \rangle. \quad (43)$$

Let  $\mathbb{Q}\langle Y \rangle$  be equipped by

1. The concatenation (or by its associated coproduct,  $\Delta_{\text{conc}}$ ).
2. The *shuffle* product, *i.e.* the commutative product defined by [47]

$$\begin{aligned} \forall w \in Y^*, \quad w \sqcup 1_{Y^*} &= 1_{Y^*} \sqcup w = w, \\ \forall x, y \in Y, \forall u, v \in Y^*, \quad xu \sqcup yv &= x(u \sqcup yv) + y(xu \sqcup v) \end{aligned}$$

or by its associated coproduct,  $\Delta_{\sqcup}$ , defined, on the letters, by

$$\forall y_k \in Y, \quad \Delta_{\sqcup} y_k = y_k \otimes 1 + 1 \otimes y_k$$

and extended by morphism. It satisfies

$$\forall u, v, w \in Y^*, \quad \langle \Delta_{\sqcup} w \mid u \otimes v \rangle = \langle w \mid u \sqcup v \rangle.$$

3. The *quasi-shuffle* product, *i.e.* the commutative product defined by [43], for any  $w \in Y^*$ ,

$$w \boxplus 1_{Y^*} = 1_{Y^*} \boxplus w = w,$$

and, for any  $y_i, y_j \in Y, \forall u, v \in Y^*$ ,

$$\begin{aligned} y_i u \boxplus y_j v &= y_j(y_i u \boxplus v) + y_i(u \boxplus y_j v) + \mu(y_i, y_j)(u \boxplus v), \\ &= y_j(y_i u \boxplus v) + y_i(u \boxplus y_j v) + y_{i+j}(u \boxplus v) \end{aligned}$$

or by its associated coproduct,  $\Delta_{\boxplus}$ , defined, on the letters, by

$$\forall y_k \in Y, \quad \Delta_{\boxplus} y_k = \Delta_{\sqcup} y_k + \Delta_+ y_k$$

and extended by morphism. It satisfies

$$\forall u, v, w \in Y^*, \quad \langle \Delta_{\boxplus} w \mid u \otimes v \rangle = \langle w \mid u \boxplus v \rangle.$$

Note that  $\Delta_{\boxplus}$  and  $\Delta_{\sqcup}$  are morphisms for the concatenation (by definition) whereas  $\Delta_+$  is not a morphism for the product of  $\mathbf{k}Y$  (for example  $\Delta_+(y_1^2) = y_1 \otimes y_1$ , whereas  $\Delta_+(y_1)^2 = 0$ ).

Hence, with the counit  $\mathbf{e}$  defined by

$$\forall P \in \mathbb{Q}\langle Y \rangle, \quad \mathbf{e}(P) = \langle P \mid 1_{Y^*} \rangle, \quad (44)$$

one gets two pairs of mutually dual bialgebras

$$\mathcal{H}_{\sqcup} = (\mathbb{Q}\langle Y \rangle, \text{conc}, 1_{Y^*}, \Delta_{\sqcup}, \mathbf{e}) \quad \text{and} \quad \mathcal{H}_{\sqcup}^{\vee} = (\mathbb{Q}\langle Y \rangle, \sqcup, 1_{Y^*}, \Delta_{\text{conc}}, \mathbf{e}) \quad (45)$$

$$\mathcal{H}_{\sqcup} = (\mathbb{Q}\langle Y \rangle, \text{conc}, 1_{Y^*}, \Delta_{\sqcup}, \mathbf{e}) \quad \text{and} \quad \mathcal{H}_{\sqcup}^{\vee} = (\mathbb{Q}\langle Y \rangle, \sqcup, 1_{Y^*}, \Delta_{\text{conc}}, \mathbf{e}) \quad (46)$$

As in (26-27), one has

$$\mathcal{D}_Y = \sum_{w \in Y^*} w \otimes w \quad (47)$$

$$= \sum_{l \in \mathcal{L}ynY} l \otimes l + \sum_{w \notin \mathcal{L}ynY} w \otimes w \quad (48)$$

$$= \prod_{l \in \mathcal{L}ynY} \exp(l \otimes l). \quad (49)$$

By the CQMM theorem (see [5]), the connected  $\mathbb{N}$ -graded, co-commutative Hopf algebra  $\mathcal{H}_{\sqcup}$  is isomorphic to the enveloping algebra of the Lie algebra of its primitive elements which is equal to  $\mathcal{L}ie_{\mathbb{Q}}\langle Y \rangle$  :

$$\mathcal{H}_{\sqcup} \cong \mathcal{U}(\mathcal{L}ie_{\mathbb{Q}}\langle Y \rangle) \quad \text{and} \quad \mathcal{H}_{\sqcup}^{\vee} \cong \mathcal{U}(\mathcal{L}ie_{\mathbb{Q}}\langle Y \rangle)^{\vee}. \quad (50)$$

Hence, let us consider [8]

1. the PBW-Lyndon basis  $\{p_w\}_{w \in Y^*}$  for  $\mathcal{U}(\mathcal{L}ie_{\mathbb{Q}}\langle Y \rangle)$  constructed recursively

$$\begin{cases} p_y = y & \text{for } y \in Y, \\ p_l = [p_s, p_r] & \text{for } l \in \mathcal{L}ynY, \text{ standard factorization of } l = (s, r), \\ p_w = p_{l_1}^{i_1} \dots p_{l_k}^{i_k} & \text{for } w = l_1^{i_1} \dots l_k^{i_k}, l_1 > \dots > l_k, l_1, \dots, l_k \in \mathcal{L}ynY, \end{cases}$$

2. and, by duality<sup>11</sup>, the linear basis  $\{s_w\}_{w \in Y^*}$  for  $(\mathbb{Q}\langle Y \rangle, \sqcup, 1_{Y^*})$ , *i.e.*

$$\forall u, v \in Y^*, \quad \langle p_u \mid s_v \rangle = \delta_{u,v}.$$

This basis can be computed recursively as follows [47]

$$\begin{cases} s_y = y, & \text{for } y \in Y, \\ s_l = y s_u, & \text{for } l = yu \in \mathcal{L}ynY, \\ s_w = \frac{s_{l_1}^{\sqcup i_1} \sqcup \dots \sqcup s_{l_k}^{\sqcup i_k}}{i_1! \dots i_k!} & \text{for } w = l_1^{i_1} \dots l_k^{i_k}, l_1 > \dots > l_k. \end{cases}$$

<sup>11</sup>The dual family (i.e. the set of coordinate forms) of a basis lies in the algebraic dual which is here the space of noncommutative series, but as the enveloping algebra under consideration is graded in finite dimensions (here by the multidegree), these series are in fact (multihomogeneous) polynomials.

Hence, since  $\{p_w\}_{w \in Y^*}$  is of PBW type then, as in (38)-(40), we get also

$$\mathcal{D}_Y = \sum_{w \in Y^*} s_w \otimes p_w \quad (51)$$

$$= \sum_{l \in \mathcal{L}ynY} s_l \otimes p_l + \sum_{w \notin \mathcal{L}ynY} s_w \otimes p_w \quad (52)$$

$$= \prod_{l \in \mathcal{L}ynY} \exp(s_l \otimes p_l). \quad (53)$$

Similarly, by the CQMM theorem, the connected  $\mathbb{N}$ -graded, co-commutative Hopf algebra  $\mathcal{H}_{\boxplus}$  is isomorphic to the enveloping algebra of

$$\text{Prim}(\mathcal{H}_{\boxplus}) = \text{Im}(\pi_1) = \text{span}_{\mathbb{Q}}\{\pi_1(w) | w \in Y^*\}, \quad (54)$$

where, for any  $w \in Y^*$ ,  $\pi_1(w)$  is obtained as follows [40]

$$\pi_1(w) = w + \sum_{k \geq 2} \frac{(-1)^{k-1}}{k} \sum_{u_1, \dots, u_k \in Y^+} \langle w | u_1 \boxplus \dots \boxplus u_k \rangle u_1 \dots u_k. \quad (55)$$

Note that Equation (55) is equivalent to the following identity [40, 41]

$$w = \sum_{k \geq 0} \frac{1}{k!} \sum_{u_1, \dots, u_k \in Y^*} \langle w | u_1 \boxplus \dots \boxplus u_k \rangle \pi_1(u_1) \dots \pi_1(u_k). \quad (56)$$

In particular, for any  $y_k \in Y$ , we have successively [40, 41]

$$\pi_1(y_k) = y_k + \sum_{l \geq 2} \frac{(-1)^{l-1}}{l} \sum_{\substack{j_1, \dots, j_l \geq 1 \\ j_1 + \dots + j_l = k}} y_{j_1} \dots y_{j_l}, \quad (57)$$

$$y_n = \sum_{k \geq 1} \frac{1}{k!} \sum_{s'_1 + \dots + s'_k = n} \pi_1(y_{s'_1}) \dots \pi_1(y_{s'_k}). \quad (58)$$

Hence, by introducing the new alphabet  $\bar{Y} = \{\bar{y}\}_{y \in Y} = \{\pi_1(y)\}_{y \in Y}$ , one has

$$(\mathbb{Q}\langle \bar{Y} \rangle, \text{conc}, 1_{\bar{Y}^*}, \Delta_{\boxplus}) \cong (\mathbb{Q}\langle Y \rangle, \text{conc}, 1_{Y^*}, \Delta_{\boxplus}) \quad (59)$$

and

$$\mathcal{H}_{\boxplus} \cong \mathcal{U}(\mathcal{L}ie_{\mathbb{Q}}\langle \bar{Y} \rangle) \cong \mathcal{U}(\text{Prim}(\mathcal{H}_{\boxplus})), \quad (60)$$

$$\mathcal{H}_{\boxplus}^{\vee} \cong \mathcal{U}(\mathcal{L}ie_{\mathbb{Q}}\langle \bar{Y} \rangle)^{\vee} \cong \mathcal{U}(\text{Prim}(\mathcal{H}_{\boxplus}))^{\vee}. \quad (61)$$

By considering

1. the PBW-Lyndon basis  $\{\Pi_w\}_{w \in Y^*}$  for  $\mathcal{U}(\text{Prim}(\mathcal{H}_{\boxplus}))$  constructed recursively as follows [40]

$$\begin{cases} \Pi_y &= \pi_1(y) & \text{for } y \in Y, \\ \Pi_l &= [\Pi_s, \Pi_r] & \text{for } l \in \mathcal{L}ynY, \text{ standard factorization of } l = (s, r), \\ \Pi_w &= \Pi_{l_1}^{i_1} \dots \Pi_{l_k}^{i_k} & \text{for } w = l_1^{i_1} \dots l_k^{i_k}, l_1 > \dots > l_k, l_1, \dots, l_k \in \mathcal{L}ynY, \end{cases}$$

2. and, by duality, the linear basis  $\{\Sigma_w\}_{w \in Y^*}$  for  $(\mathbb{Q}\langle Y \rangle, \boxplus, 1_{Y^*})$ , i.e.

$$\forall u, v \in Y^*, \quad \langle \Pi_u \mid \Sigma_v \rangle = \delta_{u,v}.$$

This basis can be computed recursively as follows [4, 40]

$$\left\{ \begin{array}{ll} \Sigma_y = y & \text{for } y \in Y, \\ \Sigma_l = \sum_{\substack{\{s'_1, \dots, s'_i\} \subset \{s_1, \dots, s_k\}, l_1 \geq \dots \geq l_n \in \mathcal{L}_{ynY} \\ (y_{s_1} \dots y_{s_k}) \stackrel{*}{=} (y_{s'_1} \dots y_{s'_n}, l_1, \dots, l_n)}} \frac{1}{i!} y_{s'_1} + \dots + s'_i \Sigma_{l_1 \dots l_n} & \text{for } l \in \mathcal{L}_{ynY} \\ & l = y_{s_1} \dots y_{s_k}, \\ \Sigma_w = \frac{1}{i_1! \dots i_k!} \Sigma_{l_1} \boxplus^{i_1} \boxplus \dots \boxplus \Sigma_{l_k} \boxplus^{i_k} & \text{for } l_1 > \dots > l_k \\ & w = l_1^{i_1} \dots l_k^{i_k}, \end{array} \right.$$

Hence, we get the following extended Schützenberger's factorization of  $\mathcal{D}_Y$  [40, 41]

$$\mathcal{D}_Y = \prod_{l \in \mathcal{L}_{ynY}} \exp(\Sigma_l \otimes \Pi_l). \quad (62)$$

**Proposition 1** ([40]). *Let  $\pi_Y : (\mathbb{Q} \oplus \mathbb{Q}\langle X \rangle x_1, \cdot) \rightarrow (\mathbb{Q}\langle Y \rangle, \cdot)$  be the morphism mapping  $x_0^{s_1-1} x_1 \dots x_0^{s_r-1} x_1$  to  $y_{s_1} \dots y_{s_r}$  and  $\pi_X$  be its inverse. Its extension over  $\mathbb{Q}\langle X \rangle$  verifying  $\pi_Y(p) = 0$ , for  $p \in \mathbb{Q}\langle X \rangle x_0$ , is still denoted by  $\pi_Y$ . Then*

1. *The polynomials  $\{\pi_Y P_{\pi_X l}\}_{l \in \mathcal{L}_{ynY}}$  are homogeneous in weight, linearly independent and upper triangular :*

$$\pi_Y P_{\pi_X l} = \Pi_l + \sum_{v > l, (v)=(l)} p_v v.$$

2. *For any  $w \in Y^*$ , the following polynomial, homogeneous in weight,*

$$\pi_Y P_{\pi_X w} = \Pi_w + \sum_{v > w, (v)=(w)} c_v v$$

*is of multi-degree  $(w)$  and  $\{\pi_Y P_{\pi_X w}\}_{w \in Y^*}$  forms a basis for  $\mathbb{Q}\langle Y \rangle$ .*

3. *Let  $\{\Theta_w\}_{w \in Y^*}$  be the family of polynomials, homogeneous in weight, in duality with the family  $\{\pi_Y P_{\pi_X w}\}_{w \in Y^*}$  :*

$$\forall u, v \in Y^*, \quad \langle \pi_Y P_{\pi_X u} \mid \Theta_v \rangle = \delta_{u,v}.$$

*Then, the family  $\{\Theta_w\}_{w \in Y^*}$  generates freely  $(\mathbb{Q}\langle Y \rangle, \boxplus)$  and*

$$\forall w \in Y^*, \quad \Theta_w = \Sigma_w + \sum_{v < w, (v)=(w)} d_v v.$$

**Remark 1.** *The family  $\{\Theta_l\}_{l \in \mathcal{L}_{ynY}}$  is not a transcendence basis of  $(\mathbb{Q}\langle Y \rangle, \boxplus)$  because if  $\{\Theta_l\}_{l \in \mathcal{L}_{ynY}}$  constitutes a transcendence basis of  $(\mathbb{Q}\langle Y \rangle, \boxplus)$  then, for any  $l \in \mathcal{L}_{ynY}$ ,  $\pi_Y P_{\pi_X l}$  is primitive but it is false in general.*

**Example 5** ([41]).

$$\begin{aligned}
\Pi_{y_4} &= y_4 - \frac{1}{2}y_1y_3 - \frac{1}{2}y_2y_2 - \frac{1}{2}y_3y_1 + \frac{1}{3}y_1^2y_2 + \frac{1}{3}y_1y_2y_1 + \frac{1}{3}y_2y_1^2 - \frac{1}{4}y_1^4, \\
\Pi_{y_3y_1} &= y_3y_1 - \frac{1}{2}y_2y_1^2 - y_1y_3 + \frac{1}{2}y_1^2y_2, \\
\Pi_{y_2y_2} &= y_2y_2 - \frac{1}{2}y_2y_1^2 - \frac{1}{2}y_1^2y_2 + \frac{1}{4}y_1^4, \\
\Pi_{y_2y_1^2} &= y_2y_1^2 - 2y_1y_2y_1 + y_1^2y_2, \\
\Pi_{y_1y_3} &= y_1y_3 - \frac{1}{2}y_1^2y_2 - \frac{1}{2}y_1y_2y_1 + \frac{1}{3}y_1^4, \\
\Pi_{y_1y_2y_1} &= y_1y_2y_1 - y_1^2y_2, \\
\Pi_{y_1^2y_2} &= y_1^2y_2 - \frac{1}{2}y_1^4, \\
\Pi_{y_1^4} &= y_1^4, \\
\Sigma_{y_4} &= y_4, \\
\Sigma_{y_3y_1} &= \frac{1}{2}y_4 + y_3y_1, \\
\Sigma_{y_2^2} &= \frac{1}{2}y_4 + y_2^2, \\
\Sigma_{y_2y_1^2} &= \frac{1}{6}y_4 + \frac{1}{2}y_3y_1 + \frac{1}{2}y_2y_2 + y_2y_1^2, \\
\Sigma_{y_1y_3} &= y_4 + y_3y_1 + y_1y_3, \\
\Sigma_{y_1y_2y_1} &= \frac{1}{2}y_4 + \frac{1}{2}y_3y_1 + y_2^2 + y_2y_1^2 + \frac{1}{2}y_1y_3 + y_1y_2y_1, \\
\Sigma_{y_1^2y_2} &= \frac{1}{2}y_4 + y_3y_1 + y_2^2 + y_2y_1^2 + y_1y_3 + y_1y_2y_1 + y_1^2y_2, \\
\Sigma_{y_1^4} &= \frac{1}{24}y_4 + \frac{1}{6}y_3y_1 + \frac{1}{4}y_2^2 + \frac{1}{2}y_2y_1^2 + \frac{1}{6}y_1y_3 + \frac{1}{2}y_1y_2y_1 + \frac{1}{2}y_1^2y_2 + y_1^4.
\end{aligned}$$

**Example 6** ([41]). *Let us express  $\{\pi_Y P_l\}_{l \in \mathcal{L}_{Y^{n \leq 4}}}$  in the basis  $\{\Pi_w\}_{w \in Y^*}$  :*

$l$	$\pi_Y P_l$
$x_0$	0
$x_1$	$\Pi_{y_1}$
$x_0x_1$	$\Pi_{y_2} + \frac{\Pi_{y_1^2}}{2}$
$x_0^2x_1$	$\Pi_{y_3} + \frac{\Pi_{y_2y_1}}{2} + \Pi_{y_1y_2} + \frac{\Pi_{y_1^3}}{6}$
$x_0x_1^2$	$\Pi_{y_2y_1} - 2\Pi_{y_1y_2} - \frac{\Pi_{y_1^3}}{2}$
$x_0^3x_1$	$\Pi_{y_4} + \frac{\Pi_{y_3y_1}}{2} + \Pi_{y_1y_3} + \frac{\Pi_{y_2^2}}{2} + \frac{\Pi_{y_1^2y_2} + \Pi_{y_1}\Pi_{y_2}\Pi_{y_1} + \Pi_{y_2}\Pi_{y_1^2}}{6} + \frac{\Pi_{y_1^4}}{24}$
$x_0^2x_1^2$	$\Pi_{y_3}\Pi_{y_1} - \frac{\Pi_{y_2}\Pi_{y_1^2}}{2} + \frac{\Pi_{y_1}\Pi_{y_2}\Pi_{y_1}}{2} - \Pi_{y_1^2}\Pi_{y_2} - 2\Pi_{y_2^2} - \frac{\Pi_{y_1^4}}{3}$
$x_0x_1^3$	$\Pi_{y_2}\Pi_{y_1^2} - 3\Pi_{y_1}\Pi_{y_2}\Pi_{y_1} + 3\Pi_{y_1^2}\Pi_{y_2} + \frac{\Pi_{y_1^4}}{2}$

## 2.2 Indiscernability over a class of formal power series

### 2.2.1 Residual calculus and representative series

**Definition 1.** Let  $S \in \mathbb{Q}\langle\langle X \rangle\rangle$  and let  $P \in \mathbb{Q}\langle X \rangle$ . The left (resp. right) residual of  $S$  by  $P$  is the formal power series  $P \triangleleft S$  (resp.  $S \triangleright P$ ) in  $\mathbb{Q}\langle\langle X \rangle\rangle$  defined by:

$$\langle P \triangleleft S \mid w \rangle = \langle S \mid wP \rangle \quad (\text{resp.} \quad \langle S \triangleright P \mid w \rangle = \langle S \mid Pw \rangle).$$

We straightforwardly get, for any  $P, Q \in \mathbb{Q}\langle X \rangle$ :

$$P \triangleleft (Q \triangleleft S) = PQ \triangleleft S, \quad (S \triangleright P) \triangleright Q = S \triangleright PQ, \quad (P \triangleleft S) \triangleright Q = P \triangleleft (S \triangleright Q). \quad (63)$$

In case  $x, y \in X$  and  $w \in X^*$ , we get<sup>12</sup>:

$$x \triangleleft (wy) = \delta_{x,y}w \quad \text{and} \quad xw \triangleright y = \delta_{x,y}w. \quad (64)$$

**Lemma 1.** (Reconstruction lemma) Let  $S \in \mathbb{Q}\langle\langle X \rangle\rangle$ . Then

$$S = \langle S \mid 1_{X^*} \rangle + \sum_{x \in X} x(S \triangleright x) = \langle S \mid 1_{X^*} \rangle + \sum_{x \in X} (x \triangleleft S)x.$$

**Lemma 2.** The residuals by a letter  $x$  is a derivation of  $(\mathbb{Q}\langle\langle X \rangle\rangle, \sqcup)$ :

$$x \triangleleft (u \sqcup v) = (x \triangleleft u) \sqcup v + u \sqcup (x \triangleleft v), \quad (u \sqcup v) \triangleright x = (u \triangleright x) \sqcup v + u \sqcup (v \triangleright x).$$

*Proof.* Use the recursive definitions of the shuffle product.  $\square$

Consequently,

**Lemma 3.** For any Lie polynomial  $Q \in \text{Lie}_{\mathbb{Q}}\langle X \rangle$ , the linear maps “ $Q \triangleleft$ ” and “ $\triangleright Q$ ” are derivations on  $(\mathbb{Q}[\mathcal{Lyn}X], \sqcup)$ .

*Proof.* For any  $l, l_1, l_2 \in \mathcal{Lyn}X$ , we have

$$\begin{aligned} \hat{l} \triangleleft (l_1 \sqcup l_2) &= l_1 \sqcup (\hat{l} \triangleleft l_2) + (\hat{l} \triangleleft l_1) \sqcup l_2 = l_1 \delta_{l_2, \hat{l}} + \delta_{l_1, \hat{l}} l_2, \\ (l_1 \sqcup l_2) \triangleright \hat{l} &= l_1 \sqcup (l_2 \triangleright \hat{l}) + (l_1 \triangleright \hat{l}) \sqcup l_2 = l_1 \delta_{l_2, \hat{l}} + \delta_{l_1, \hat{l}} l_2. \end{aligned}$$

$\square$

**Lemma 4.** For any Lyndon word  $l \in \mathcal{Lyn}X$  and  $\check{S}_l$  defined as in (??), one has

$$x_1 \triangleleft l = l \triangleright x_0 = 0 \quad \text{and} \quad x_1 \triangleleft \check{S}_l = \check{S}_l \triangleright x_0 = 0.$$

*Proof.* Since  $x_1 \triangleleft$  and  $\triangleright x_0$  are derivations and for any  $l \in \mathcal{Lyn}X - X$ , the polynomial  $\check{S}_l$  belongs to  $x_0 \mathbb{Q}\langle X \rangle x_1$  then the expected results follow.  $\square$

**Theorem 1.** (On representative series) The following properties are equivalent for any series  $S \in \mathbb{Q}\langle\langle X \rangle\rangle$ :

<sup>12</sup>For any words  $u$  and  $v \in X^*$ , if  $u = v$  then  $\delta_{u,v} = 1$  else 0.



- (1) The left  $\mathbb{C}$ -module  $Res_g(S) = \text{span}\{w \triangleleft S \mid w \in X^*\}$  is finite dimensional.
- (2) The right  $\mathbb{C}$ -module  $Res_d(S) = \text{span}\{S \triangleright w \mid w \in X^*\}$  is finite dimensional.
- (3) There are matrices  $\lambda \in \mathcal{M}_{1,n}(\mathbb{Q})$ ,  $\eta \in \mathcal{M}_{n,1}(\mathbb{Q})$  and a representation of  $X^*$  in  $\mathcal{M}_{n,n}$ , such that

$$\begin{aligned} S &= \sum_{w \in X^*} [\lambda \mu(w) \eta] w, \\ &= \lambda \left( \prod_{l \in \mathcal{L}yn.X} e^{\mu(S_l) P_l} \right) \eta. \end{aligned}$$

A series that satisfies the items of this theorem will be called *representative series*. This concept can be found in [1, 44, 15]. The two first items are in [19, 24]. The third item can be deduced from [7, 13] for example and it was used to factorize first time, by Lyndon words, the output of bilinear and analytical dynamical systems respectively in [26, 27] and to study polylogarithms, hypergeometric functions and associated functions in [29, 31, 38]. The dimension of  $Res_g(S)$  is equal to that of  $Res_d(S)$ , and to the minimal dimension of a representation satisfying the third point of Theorem 1. This rank is then equal to the rank of the Hankel matrix of  $S$ , that is the infinite matrix  $(\langle S \mid uv \rangle)_{u,v \in X}$  indexed by  $X^* \times X^*$  and is also called *Hankel rank* of  $S$  [19, 24]:

**Definition 2.** ([19, 24]) *The Hankel rank of a formal power series  $S \in \mathbb{C}\langle\langle X \rangle\rangle$  is the dimension of the vector space*

$$\{S \triangleright \Pi \mid \Pi \in \mathbb{C}\langle X \rangle\}, \quad (\text{resp.} \quad \{\Pi \triangleleft S \mid \Pi \in \mathbb{C}\langle X \rangle\}).$$

The triplet  $(\lambda, \mu, \eta)$  is called a *linear representation* of  $S$ . We define the minimal representation<sup>13</sup> of  $S$  as being a representation of  $S$  of minimal dimension.

For any proper series  $S$ , the following power series is called “star of  $S$ ”

$$S^* = 1 + S + S^2 + \dots + S^n + \dots \quad (65)$$

**Definition 3.** ([3, 49]) *A series  $S$  is called rational if it belongs to the closure in  $\mathbb{Q}\langle\langle X \rangle\rangle$  of the noncommutative polynomial algebra by sum, product, and star operation of proper<sup>14</sup> elements. The set of rational power series will be denoted by  $\mathbb{Q}^{rat}\langle\langle X \rangle\rangle$ .*

**Lemma 5.** *For any noncommutative rational series (resp. polynomial)  $R$  and for any polynomial  $P$ , the left and right residuals of  $R$  by  $P$  are rational (resp. polynomial).*

**Theorem 2.** (Schützenberger, [3, 49]) *Any noncommutative power series is representative if and only if it is rational.*

<sup>13</sup>It can be shown that all minimal representations are isomorphic (see [3]).

<sup>14</sup>A series  $S$  is said to be proper if  $\langle S \mid \epsilon \rangle = 0$ .

**Example 7.** Let  $S = (x_0x_1)^*$  be the rational power series over  $X = \{x_0, x_1\}$ . Since

$$S = (x_0x_1)^* = 1_{X^*} + x_0x_1 + (x_0x_1)^2 + \dots$$

then

$$\begin{aligned} S \triangleright x_0 &= x_1 + x_1x_0x_1 + \dots, \\ S \triangleright x_1 &= 0, \\ S \triangleright x_0^2 &= 0, \\ S \triangleright x_0x_1 &= S. \end{aligned}$$

The Hankel rank of  $S$  is then 3.

### 2.2.2 Continuity and indiscernability

**Definition 4.** ([25, 39]) Let  $\mathcal{H}$  be a class of formal power series over  $X$  and let  $S \in \mathbb{C}\langle\langle X \rangle\rangle$ .

(1)  $S$  is said to be continuous<sup>15</sup> over  $\mathcal{H}$  if for any  $\Phi \in \mathcal{H}$ , the following sum, denoted by  $\langle S \parallel \Phi \rangle$ , is convergent in norm

$$\sum_{w \in X^*} \langle S \mid w \rangle \langle \Phi \mid w \rangle.$$

The set of continuous power series over  $\mathcal{H}$  will be denoted by  $\mathbb{C}^{\text{cont}}\langle\langle X \rangle\rangle$ .

(2)  $S$  is said to be indiscernable<sup>16</sup> over  $\mathcal{H}$  if and only if

$$\forall \Phi \in \mathcal{H}, \quad \langle S \parallel \Phi \rangle = 0.$$

**Lemma 6.** Let  $\mathcal{H}$  be a monoid containing  $\{e^{tx}\}_{x \in X}^{t \in \mathbb{C}}$ . Let  $S \in \mathbb{C}^{\text{cont}}\langle\langle X \rangle\rangle$  be indiscernable over  $\mathcal{H}$ . Then for any  $x \in X$ ,  $x \triangleleft S$  and  $S \triangleright x$  belong to  $\mathbb{C}^{\text{cont}}\langle\langle X \rangle\rangle$  and they are indiscernable over  $\mathcal{H}$ .

*Proof.* Let us calculate  $\langle x \triangleleft S \parallel \Phi \rangle = \langle S \parallel \Phi x \rangle$  and  $\langle S \triangleright x \parallel \Phi \rangle = \langle S \parallel x \Phi \rangle$ . Since

$$\lim_{t \rightarrow 0} \frac{e^{tx} - 1}{t} = x \quad \text{and} \quad \lim_{t \rightarrow 0} \frac{e^{tx} - 1}{t} = x$$

then, for any  $\Phi \in \mathcal{H}$ , by uniform convergence, one has

$$\begin{aligned} \langle S \parallel \Phi x \rangle &= \langle S \parallel \lim_{t \rightarrow 0} \Phi \frac{e^{tx} - 1}{t} \rangle = \lim_{t \rightarrow 0} \langle S \parallel \Phi \frac{e^{tx} - 1}{t} \rangle, \\ \langle S \parallel x \Phi \rangle &= \langle S \parallel \lim_{t \rightarrow 0} \frac{e^{tx} - 1}{t} \Phi \rangle = \lim_{t \rightarrow 0} \langle S \parallel \frac{e^{tx} - 1}{t} \Phi \rangle. \end{aligned}$$

<sup>15</sup>See [25, 39] for a convergence criterion and an example of continuous generating series.

<sup>16</sup>Here, we adapt this notion developed in [25] via the residual calculus.

Since  $S$  is indiscernable over  $\mathcal{H}$  then

$$\begin{aligned}\langle S \parallel \Phi x \rangle &= \lim_{t \rightarrow 0} \frac{1}{t} \langle S \parallel \Phi e^{tx} \rangle - \lim_{t \rightarrow 0} \frac{1}{t} \langle S \parallel \Phi \rangle = 0, \\ \langle S \parallel x \Phi \rangle &= \lim_{t \rightarrow 0} \frac{1}{t} \langle S \parallel e^{tx} \Phi \rangle - \lim_{t \rightarrow 0} \frac{1}{t} \langle S \parallel \Phi \rangle = 0.\end{aligned}$$

□

**Proposition 2.** *Let  $\mathcal{H}$  be a monoid containing  $\{e^{tx}\}_{x \in X}^{t \in \mathbb{C}}$ . The formal power series  $S \in \mathbb{C}^{\text{cont}} \langle\langle X \rangle\rangle$  is indiscernable over  $\mathcal{H}$  if and only if  $S = 0$ .*

*Proof.* If  $S = 0$  then it is immediate that  $S$  is indiscernable over  $\mathcal{H}$ . Conversely, if  $S$  is indiscernable over  $\mathcal{H}$  then by Lemma 6, for any word  $w \in X^*$  and, by induction on the length of  $w$ ,  $w \triangleleft S$  is indiscernable over  $\mathcal{H}$ . In particular,

$$\langle w \triangleleft S \parallel \text{Id}_{\mathcal{H}} \rangle = \langle S \mid w \rangle = 0.$$

In other words,  $S = 0$ . □

## 2.3 Polylogarithms and harmonic sums

### 2.3.1 Structures of polylogarithms and harmonic sums

Let  $Y$  be the infinite alphabet  $\{y_i\}_{i \geq 1}$  equipped with the order  $y_1 > y_2 > y_3 > \dots$  and let  $\mathcal{Lyn}Y$  be the set of Lyndon words over  $Y$ . The length of  $w = y_{s_1} \dots y_{s_r} \in Y^*$  is denoted by  $|w|$  and its degree equals  $s_1 + \dots + s_r$ .

Let  $X$  be the finite alphabet  $\{x_0, x_1\}$  equipped with the order  $x_0 < x_1$  and

$$\mathcal{C} := \mathbb{C} \left[ z, \frac{1}{z}, \frac{1}{1-z} \right] \quad \text{and} \quad \mathcal{G} := \left\{ z, \frac{1}{z}, \frac{z-1}{z}, \frac{z}{z-1}, \frac{1}{1-z}, 1-z \right\} \quad (66)$$

This ring  $\mathcal{C}$  is invariant under differentiation and under the homographic transformations belonging to the group  $\mathcal{G}$  whose elements commute the singularities  $\{0, 1, +\infty\}$ . The iterated integral over  $\omega_0, \omega_1$  associated to the word  $w = x_{i_1} \dots x_{i_k}$  over  $X^*$  (the monoid generated by  $X$ ) and along the integration path  $z_0 \rightsquigarrow z$  is the following multiple integral defined by

$$\int_{z_0 \rightsquigarrow z} \omega_{i_1} \dots \omega_{i_k} = \int_{z_0}^z \omega_{i_1}(t_1) \int_{z_0}^{t_1} \omega_{i_2}(t_2) \dots \int_{z_0}^{t_{r-1}} \omega_{i_r}(t_r), \quad (67)$$

where  $t_1 \dots t_{r-1}$  is a subdivision of the path  $z_0 \rightsquigarrow z$ . In a shortened notation, we denote this integral by  $\alpha_{z_0}^z(w)$  and<sup>17</sup>  $\alpha_{z_0}^z(1_{X^*}) = 1$ . One can check that the polylogarithm  $\text{Li}_{s_1, \dots, s_r}$  is also the value of the iterated integral over  $\omega_0, \omega_1$  and along the integration path  $0 \rightsquigarrow z$  [29, 31]:

$$\text{Li}_w(z) = \alpha_0^z(x_0^{s_1-1} x_1 \dots x_0^{s_r-1} x_1). \quad (68)$$

<sup>17</sup>Here,  $1_{X^*}$  stands for the empty word over  $X$ .

**Example 8.**

$$\begin{aligned}
\alpha_0^z(x_0x_1) &= \int_0^z \frac{ds}{s} \int_0^s \frac{dt}{1-t} \\
&= \int_0^z \frac{ds}{s} \int_0^s dt \sum_{k \geq 0} t^k \\
&= \sum_{k \geq 1} \int_0^z ds \frac{s^{k-1}}{k} \\
&= \sum_{k \geq 1} \frac{z^k}{k^2} \\
&= \text{Li}_2(z).
\end{aligned}$$

The definition of polylogarithms is extended over the words  $w \in X^*$  by putting  $\text{Li}_{x_0}(z) := \log(z)$ . Thus,  $\{\text{Li}_w\}_{w \in X^*}$ , and then  $\{\text{P}_w(z) := (1-z)^{-1} \text{Li}_w(z)\}_{w \in Y^*}$ , are  $\mathbb{C}$ -linearly independent [35, 32]. Since, for any  $v = y_{s_1} \dots y_{s_r} \in Y^*$ ,  $\text{P}_v$  is the ordinary generating function of the sequence  $\{\text{H}_v(N)\}_{N \geq 0}$  [37]:

$$\text{P}_v(z) = \sum_{N \geq 0} \text{H}_v(N) z^N, \quad \text{with} \quad \text{H}_v(N) = \sum_{N \geq n_1 > \dots > n_r > 0} \frac{1}{n_1^{s_1} \dots n_r^{s_r}} \quad (69)$$

then, as a consequence of the classical isomorphism between convergent Taylor series and their associated sums, the harmonic sums  $\{\text{H}_w\}_{w \in Y^*}$  are also  $\mathbb{C}$ -linearly independent. Firstly,  $\ker \text{P} = \{0\}$  and  $\ker \text{H} = \{0\}$ , and secondly,  $\text{P}$  is a morphism for the Hadamard product:

$$\text{P}_u(z) \odot \text{P}_v(z) = \sum_{N \geq 0} \text{H}_u(N) \text{H}_v(N) z^N = \sum_{N \geq 0} \text{H}_{u \boxtimes v}(N) z^N = \text{P}_{u \boxtimes v}(z). \quad (70)$$

**Proposition 3.** ([37]) *Extended by linearity, the map*

$$\begin{aligned}
\text{P} : (\mathbb{C}\langle Y \rangle, \boxtimes) &\longrightarrow (\mathbb{C}\{\text{P}_w\}_{w \in Y^*}, \odot), \\
u &\longmapsto \text{P}_u
\end{aligned}$$

*is an isomorphism of algebras. Moreover, the map*

$$\begin{aligned}
\text{H} : (\mathbb{C}\langle Y \rangle, \boxtimes) &\longrightarrow (\mathbb{C}\{\text{H}_w\}_{w \in Y^*}, \cdot), \\
u &\longmapsto \text{H}_u = \{\text{H}_u(N)\}_{N \geq 0}
\end{aligned}$$

*is an isomorphism of algebras.*

Studying the equivalence between action of  $\{(1-z)^l\}_{l \in \mathbb{Z}}$  over  $\{\text{P}_w(z)\}_{w \in Y^*}$  and that of  $\{N^k\}_{k \in \mathbb{Z}}$  over  $\{\text{H}_w(N)\}_{w \in Y^*}$  (see [17]), we have

**Theorem 3.** ([39]) *The Hadamard  $\mathcal{C}$ -algebra of  $\{\text{P}_w\}_{w \in Y^*}$  can be identified with that of  $\{\text{P}_l\}_{l \in \mathcal{L}_{\text{yn}} Y}$ . In the same way, the algebra of harmonic sums  $\{\text{H}_w\}_{w \in Y^*}$  with polynomial coefficients can be identified with that of  $\{\text{H}_l\}_{l \in \mathcal{L}_{\text{yn}} Y}$ .*

### 2.3.2 Results à la Abel for noncommutative generating and global regularizations

Let  $L$  and  $H$  be the noncommutative generating series of respectively  $\{Li_w\}_{w \in X^*}$  and  $\{H_w(N)\}_{w \in Y^*}$  [35, 37]:

$$L = \sum_{w \in X^*} Li_w w \quad \text{and} \quad H = \sum_{w \in Y^*} H_w w. \quad (71)$$

Hence,  $L$  and  $H$  are image, by the tensor products  $Li \otimes \text{Id}$  and  $H \otimes \text{Id}$ , of the diagonal series  $\mathcal{D}_X$  and  $\mathcal{D}_Y$  respectively. We get

**Theorem 4** (Factorization of  $L$  and of  $H$ , [35, 32, 40]). *Let*

$$L_{\text{reg}} = \prod_{l \in \mathcal{L}ynX-X}^{\searrow} e^{Li_{S_l} P_l} \quad \text{and} \quad H_{\text{reg}}(N) = \prod_{l \in \mathcal{L}ynY-\{y_1\}}^{\searrow} e^{H_{\Sigma_l(N)} \Sigma_l}.$$

Then  $L(z) = e^{-x_1 \log(1-z)} L_{\text{reg}}(z) e^{x_0 \log z}$  and  $H(N) = e^{H_{y_1(N)} y_1} H_{\text{reg}}(N)$ .

For any  $l \in \mathcal{L}ynX-X$  (resp.  $\mathcal{L}ynY-\{y_1\}$ ), the polynomial  $S_l$  (resp.  $\Sigma_l$ ) is a finite combination of words in  $x_0 X^* x_1$  (resp.  $Y^* - y_1 Y^*$ ). Then we can state the following

**Proposition 4** ([40]). *Let  $Z_{\sqcup} := L_{\text{reg}}(1)$  and  $Z_{\boxplus} := H_{\text{reg}}(\infty)$ .*

*Then  $Z_{\sqcup}$  and  $Z_{\boxplus}$  are group-like, for  $\Delta_{\sqcup}$  and  $\Delta_{\boxplus}$  respectively.*

**Proposition 5** (Successive differentiations of  $L$ , [38]). *Let  $\partial_z = d/dz$  and let  $\theta_0 = zd/dz$ . For any  $n \in \mathbb{N}$ , we have*

$$\partial_z^n L(z) = D_n(z) L(z) \quad \text{and} \quad \theta_0^n L(z) = E_n(z) L(z),$$

where<sup>18</sup>

- the polynomials  $D_n(z)$  and  $E_n(z)$  in  $\mathcal{C}\langle X \rangle$  are defined as follows

$$D_n(z) = \sum_{\text{wgt}(\mathbf{r})=n} \sum_{w \in X^{\text{deg}(\mathbf{r})}} \prod_{i=1}^{\text{deg}(\mathbf{r})} \binom{\sum_{j=1}^i r_j + j - 1}{r_i} \tau_{\mathbf{r}}(w),$$

$$E_n(z) = \sum_{\text{wgt}(\mathbf{r})=n} \sum_{w \in X^{\text{deg}(\mathbf{r})}} \prod_{i=1}^{\text{deg}(\mathbf{r})} \binom{\sum_{j=1}^i r_j + j - 1}{r_i} \rho_{\mathbf{r}}(w),$$

- for any  $w = x_{i_1} \cdots x_{i_k}$  and  $\mathbf{r} = (r_1, \dots, r_k)$  of degree  $\text{deg}(\mathbf{r}) = k$  and of weight  $\text{wgt}(\mathbf{r}) = k + r_1 + \cdots + r_k$ , the polynomials  $\tau_{\mathbf{r}}(w) = \tau_{r_1}(x_{i_1}) \cdots \tau_{r_k}(x_{i_k})$  and  $\rho_{\mathbf{r}}(w) = \rho_{r_1}(x_{i_1}) \cdots \rho_{r_k}(x_{i_k})$  are defined respectively by, for any  $r \in \mathbb{N}$ ,

$$\tau_r(x_0) = \partial_z^r \frac{x_0}{z} = \frac{-r! x_0}{(-z)^{r+1}} \quad \text{and} \quad \tau_r(x_1) = \partial_z^r \frac{x_1}{1-z} = \frac{r! x_1}{(1-z)^{r+1}},$$

$$\rho_r(x_0) = \theta_0^r \frac{x_0}{z} = 0 \quad \text{and} \quad \rho_r(x_1) = \theta_0^r \frac{z x_1}{1-z} = \text{Li}_{-r}(z) x_1.$$

<sup>18</sup>Consider also  $\theta_1 = (1-z)d/dz$ . But  $\theta_0 + \theta_1 = \partial_z$  and then  $\theta_1^n L(z) = [D_n(z) - E_n(z)]L(z)$ .

**Example 9** (Coefficients of  $\theta_0^n \text{Li}$ ). *Since, for any  $w \in X^+$ , one has*

$$\theta_0 \text{Li}_w = \begin{cases} \text{Li}_u & \text{if } w = x_0 u, \\ \text{Li}_0 \text{Li}_u & \text{if } w = x_1 u. \end{cases}$$

*then one obtains, for example*

- For any  $n \geq 1$  and for any  $w \in X^*$ , one has

$$\theta_0^n \text{Li}_{x_0^n w}(z) = \text{Li}_w(z).$$

*In particular,*

$$\theta_0^n \text{Li}_{x_0^n}(z) = 1.$$

- Letting  $E(n, m)$  denote the Eulerian numbers :

$$E(n, m) = \sum_{j=0}^m (-1)^j \binom{n+1}{j} (m+1-j)^n,$$

*one has, for any  $n \geq 0$ ,*

$$\theta_0^{n+1} \text{Li}_{x_1}(z) = \frac{z}{(1-z)^{n+1}} \sum_{m=0}^n E(n, m) x^m =: \text{Li}_{-n}(z).$$

*In particular,*

$$\theta_0 \text{Li}_{x_1}(z) = \frac{z}{(1-z)} = \text{Li}_0(z).$$

- For any  $k \in \mathbb{N}^*$ , one has

$$\theta_0^k \text{Li}_{x_1^2}(z) = \sum_{j=0}^{k-1} \binom{k-1}{j} \text{Li}_{-j}(z) \text{Li}_{2+j-k}(z).$$

*For example*

$$\begin{aligned} \theta_0 \text{Li}_{x_1^2}(z) &= \text{Li}_0(z) \text{Li}_1(z), \\ \theta_0^2 \text{Li}_{x_1^2}(z) &= \text{Li}_{-1}(z) \text{Li}_1(z) + \text{Li}_0^2(z), \\ \theta_0^3 \text{Li}_{x_1^2}(z) &= \text{Li}_{-2}(z) \text{Li}_1(z) + 3 \text{Li}_{-1}(z) \text{Li}_0(z), \\ \theta_0^4 \text{Li}_{x_1^2}(z) &= \text{Li}_{-3}(z) \text{Li}_1(z) + 4 \text{Li}_{-2}(z) \text{Li}_0(z) + 3 \text{Li}_{-1}^2(z), \\ &\vdots \end{aligned}$$

The noncommutative generating series of polylogarithms [35, 32] satisfies the differential equation

$$dL = (x_0\omega_0 + x_1\omega_1)L \quad (72)$$

with boundary condition

$$L(z) \underset{z \rightarrow 0}{\rightsquigarrow} \exp(x_0 \log z) \quad \text{and} \quad L(z) \underset{z \rightarrow 1}{\rightsquigarrow} \exp(-x_1 \log(1-z)) Z_{\sqcup}. \quad (73)$$

This implies  $L$  is the exponential of a Lie series [35, 32]. Hence [38],

$$\log L(z) = \sum_{k \geq 1} \frac{(-1)^{k-1}}{k} \sum_{u_1, \dots, u_k \in X^+} \text{Li}_{u_1 \sqcup \dots \sqcup u_k}(z) u_1 \dots u_k \quad (74)$$

$$= \sum_{w \in X^*} \text{Li}_w(z) \pi_1(w). \quad (75)$$

**Proposition 6** ([38]). *Let  $G(z), H(z)$  be exponential solutions of (72). Then there exists a constant Lie series  $C$  such that  $G(z) = H(z)e^C$ .*

**Theorem 5** ([38]). *Let  $\text{Gal}_{\mathbb{C}}(DE)$  be the differential Galois group associated to the Drinfel'd equation. Then  $\text{Gal}_{\mathbb{C}}(DE) = \{e^C \mid C \in \text{Lie}_{\mathbb{C}}\langle\langle X \rangle\rangle\}$  and it contains the monodromy group defined as follows*

$$\mathcal{M}_0 L = L e^{2i\pi \mathbf{m}_0} \quad \text{and} \quad \mathcal{M}_1 L = L Z_{\sqcup}^{-1} e^{-2i\pi x_1} Z_{\sqcup} = L e^{2i\pi \mathbf{m}_1},$$

$$\text{where } \mathbf{m}_0 = x_0 \quad \text{and} \quad \mathbf{m}_1 = \prod_{l \in \text{Lyn} X - X}^{\searrow} e^{-\zeta(S_l) \text{ad}_{P_l}(-x_1)}.$$

Let us call  $\text{LI}_{\mathcal{C}}$  the smallest algebra containing  $\mathcal{C}$ , closed under derivation and under integration with respect to  $\omega_0$  and  $\omega_1$ . It is the  $\mathcal{C}$ -module generated by the polylogarithms  $\{\text{Li}_w\}_{w \in X^*}$ .

Let  $\Lambda(z) := \pi_Y L(z)$ . Then [39]

$$\Lambda(z) \underset{z \rightarrow 1}{\rightsquigarrow} \exp\left(y_1 \log \frac{1}{1-z}\right) \pi_Y Z_{\sqcup}. \quad (76)$$

Since the coefficient of  $z^N$  in the ordinary Taylor expansion of  $P_{y_1^k}(z)$  is  $H_{y_1^k}(N)$  then let us put [39]

$$\text{Mono}(z) := e^{-(x_1+1) \log(1-z)} = \sum_{k \geq 0} P_{y_1^k}(z) y_1^k \quad (77)$$

$$\text{Const} := \sum_{k \geq 0} H_{y_1^k} y_1^k = \exp\left(-\sum_{k \geq 1} H_{y_k} \frac{(-y_1)^k}{k}\right). \quad (78)$$

We put also<sup>19</sup> [39]

$$B(y_1) := \exp\left(\sum_{k \geq 1} \zeta(y_k) \frac{(-y_1)^k}{k}\right) \quad \text{and} \quad B'(y_1) := \exp(\gamma y_1) B(y_1). \quad (79)$$

<sup>19</sup>Here, the coefficient  $\langle B(y_1) \mid y_1^k \rangle$  corresponds to the Euler–Mac Laurin constant associated to  $\langle \text{Const}(N) \mid y_1^k \rangle$ , i.e. the finite party of its asymptotic expansion in the scale of comparison  $\{n^a \log^b(n)\}_{a \in \mathbb{Z}, b \in \mathbb{N}}$ .

As a consequence of (76)-(78), one gets

**Theorem 6** ([39]).

$$\pi_Y P(z) \underset{z \rightarrow 1}{\widetilde{}} \text{Mono}(z) \pi_Y Z_{\sqcup} \quad \text{and} \quad H(N) \underset{N \rightarrow \infty}{\widetilde{}} \text{Const}(N) \pi_Y Z_{\sqcup}.$$

Or equivalently,

$$\lim_{z \rightarrow 1} \exp\left(y_1 \log \frac{1}{1-z}\right) \Lambda(z) = \lim_{N \rightarrow \infty} \exp\left(\sum_{k \geq 1} H_{y_k}(N) \frac{(-y_1)^k}{k}\right) H(N) = \pi_Y Z_{\sqcup}.$$

**Theorem 7** ([17]). For any  $g \in \mathcal{C}\{P_w\}_{w \in Y^*}$ , there exist algorithmically computable coefficients  $c_j \in \mathbb{C}$ ,  $\alpha_j \in \mathbb{Z}$ ,  $\beta_j \in \mathbb{N}$  such that

$$g(z) \sim \sum_{j=0}^{+\infty} c_j (1-z)^{\alpha_j} \log^{\beta_j}(1-z) \quad \text{for } z \rightarrow 1,$$

and the coefficients  $b_i \in \mathbb{C}$ ,  $\eta_i \in \mathbb{Z}$ ,  $\kappa_i \in \mathbb{N}$  such that

$$\langle g(z) \mid z^n \rangle \sim \sum_{i=0}^{+\infty} b_i n^{\eta_i} \log^{\kappa_i}(n) \quad \text{for } n \rightarrow \infty.$$

Theorem 7 means also that the  $\{P_w\}_{w \in Y^*}$  admit a full singular expansion, at  $z = 1$ , and then their ordinary Taylor coefficients,  $\{H_w(N)\}_{w \in Y^*}$  admit a full asymptotic expansion, for  $N \rightarrow +\infty$ . More precisely,

**Corollary 1.** For any  $w \in Y^*$  and for any  $k \geq 1$ , we have

$$H_w(N) = \sum_{i=1}^{|w|} \alpha_i \log^i(N) + \gamma_w + \sum_{j=1}^k \sum_{i=0}^{|w|-1} \beta_{i,j} \frac{1}{N^j} \log^i(N) + O\left(\frac{1}{N^k}\right).$$

where the coefficients  $\gamma_w$ ,  $\alpha_i$  and  $\beta_{i,j}$  belong to the  $\mathbb{Q}[\gamma]$ -algebra generated by convergent polyzetas.

More generally, by Theorem 5, we get

**Proposition 7.** For any commutative  $\mathbb{Q}$ -algebra  $A$  and for any Lie series  $C \in \mathcal{L}ie_A\langle X \rangle$ , let

$$\bar{L} = Le^C, \quad \bar{\Lambda} = \pi_Y \bar{L}, \quad \bar{P}(z) = \frac{\bar{\Lambda}(z)}{1-z}.$$

Then

1.  $\bar{Z}_{\sqcup} = Z_{\sqcup} e^C$  is group-like, for the co-product  $\Delta_{\sqcup}$ ,
2.  $\bar{L}(z) \underset{z \rightarrow 1}{\widetilde{}} \exp(-x_1 \log(1-z)) \bar{Z}_{\sqcup}$ ,
3.  $\bar{P}(z) \underset{z \rightarrow 1}{\widetilde{}} \text{Mono}(z) \pi_Y \bar{Z}_{\sqcup}$ ,



$$4. \overline{\mathbb{H}}(N) \underset{N \rightarrow \infty}{\widetilde{\longrightarrow}} \text{Const}(N) \pi_Y \overline{Z}_{\sqcup},$$

where, for any  $w \in Y^*$  and  $N \geq 0$ , one defines the coefficient  $\langle \overline{\mathbb{H}}(N) \mid w \rangle$  of  $w$  in the power series  $\overline{\mathbb{H}}(N)$  as the coefficient  $\langle \overline{\mathbb{P}}_w(z) \mid z^N \rangle$  of  $z^N$  in the ordinary Taylor expansion of the polylogarithmic function  $\overline{\mathbb{P}}_w(z)$ .

By Proposition 7, we get successively

**Proposition 8** ([33]). *Let  $\overline{\zeta}_{\sqcup}$  and  $\overline{\zeta}_{\sqcup\sqcup}$  be the characters of respectively  $(A\langle X \rangle, \sqcup)$  and  $(A\langle Y \rangle, \sqcup\sqcup)$  satisfying*

$$\overline{\zeta}_{\sqcup}(x_0) = \overline{\zeta}_{\sqcup}(x_1) = 0 \quad \text{and} \quad \overline{\zeta}_{\sqcup\sqcup}(y_1) = 0.$$

Then

$$\begin{aligned} \sum_{w \in Y^*} \overline{\zeta}_{\sqcup}(w) w = \overline{Z}_{\sqcup} &= \prod_{l \in \mathcal{L}ynX-X}^{\rightarrow} \exp(\overline{\zeta}(S_l) P_l), \\ \sum_{w \in Y^*} \overline{\zeta}_{\sqcup\sqcup}(w) w = \overline{Z}_{\sqcup\sqcup} &= \prod_{l \in \mathcal{L}ynY-\{y_1\}}^{\rightarrow} \exp(\overline{\zeta}(\Sigma_l) \Pi_l). \end{aligned}$$

**Proposition 9.** *Let  $\{\overline{\gamma}_w\}_{w \in Y^*}$  be the Euler–Mac Laurin constants associated to  $\{\overline{\mathbb{H}}_w(N)\}_{w \in Y^*}$ . Let  $\overline{Z}_\gamma$  be its noncommutative generating series. Then,*

1. *The following map realizes a character :*

$$\begin{aligned} \overline{\gamma}_\bullet &: (A\langle Y \rangle, \sqcup\sqcup) \longrightarrow (\mathbb{R}, \cdot), \\ w &\longmapsto \langle \overline{\gamma}_\bullet \mid w \rangle = \overline{\gamma}_w. \end{aligned}$$

2. *The noncommutative power series  $\overline{Z}_\gamma$  is group-like, for  $\Delta_{\sqcup\sqcup}$ .*

3. *There exists a group-like element  $\overline{Z}_{\sqcup\sqcup}$ , for the co-product  $\Delta_{\sqcup\sqcup}$ , such that*

$$\overline{Z}_\gamma = \sum_{w \in Y^*} \overline{\gamma}_w w = \exp(\gamma y_1) \overline{Z}_{\sqcup\sqcup}.$$

By Theorem 6, Propositions 7 and 9, we also get

**Proposition 10.** *For any  $C \in \mathcal{L}ie_A\langle X \rangle$  such that  $\overline{Z}_{\sqcup} = Z_{\sqcup} e^C$ . Then*

$$\overline{Z}_\gamma = B(y_1) \pi_Y \overline{Z}_{\sqcup}, \quad \text{or equivalently by cancellation,} \quad \overline{Z}_{\sqcup\sqcup} = B'(y_1) \pi_Y \overline{Z}_{\sqcup},$$

where  $B(y_1)$  and  $B'(y_1)$  are given in (79).

By Propositions 7, the noncommutative generating series  $\overline{Z}_{\sqcup}$  and  $\overline{Z}_{\sqcup\sqcup}$  are group-like, for the co-product  $\Delta_{\sqcup}$  and  $\Delta_{\sqcup\sqcup}$  respectively, and we also have

$$\overline{Z}_{\sqcup} = \sum_{l \in \mathcal{L}ynX-X} \overline{\zeta}(S_l) P_l + \sum_{w \notin \mathcal{L}ynX-X} \overline{\zeta}_{\sqcup}(S_w) P_w, \quad (80)$$

$$\overline{Z}_{\sqcup\sqcup} = \sum_{l \in \mathcal{L}ynY-\{y_1\}} \overline{\zeta}(\Sigma_l) \Pi_l + \sum_{w \notin \mathcal{L}ynY-\{y_1\}} \overline{\zeta}_{\sqcup\sqcup}(\Sigma_w) \Pi_w. \quad (81)$$

Hence, by Proposition 10, we deduce in particular,

$$\sum_{l \in \mathcal{L}_{ynY-\{y_1\}}} \bar{\zeta}(\Sigma_l) \Pi_l + \dots = B'(y_1) \sum_{l \in \mathcal{L}_{ynX-X}} \bar{\zeta}(S_l) \pi_Y P_l + \dots \quad (82)$$

By Proposition 1, the elements of the family  $\{\pi_Y P_l\}_{l \in \mathcal{L}_{ynX}}$  are decomposable in the linear basis  $\{\Pi_w\}_{w \in Y^*}$  of  $\mathcal{U}(\text{Prim}(\mathcal{H}_{\underline{\mathbf{1}}}))$ . Thus, by identification of locale coordinates, *i.e.* the coefficients of  $\{\Pi_l\}_{l \in \mathcal{L}_{ynY-\{y_1\}}}$ , we get the homogenous polynomial relations among convergent polyzetas [40].

### 3 Polysystem and differential realization

#### 3.1 Polysystem and convergence criterion

##### 3.1.1 Serial estimates from above

Here, generalizing a little,  $\mathbb{K}$  is supposed a  $\mathbb{C}$ -algebra and a complete normed vector space equipped with a norm denoted by  $\|\cdot\|$ .

For any  $n \in \mathbb{N}$ ,  $X^{\geq n}$  denotes the set of words over  $X$  of length greater than or equal to  $n$ . The set of formal power series (resp. polynomials) on  $X$ , is denoted by  $\mathbb{K}\langle\langle X \rangle\rangle$  (resp.  $\mathbb{K}\langle X \rangle$ ).

**Definition 5.** ([25, 39]) *Let  $\xi, \chi$  be real positive functions over  $X^*$ . Let  $S \in \mathbb{K}\langle\langle X \rangle\rangle$ .*

(1)  *$S$  will be said  $\xi$ -exponentially bounded from above if it verifies*

$$\exists K \in \mathbb{R}_+, \exists n \in \mathbb{N}, \forall w \in X^{\geq n}, \quad \|\langle S \mid w \rangle\| \leq K \frac{\xi(w)}{|w|!}.$$

*We denote by  $\mathbb{K}^{\xi\text{-em}}\langle\langle X \rangle\rangle$  the set of formal power series in  $\mathbb{K}\langle\langle X \rangle\rangle$  which are  $\xi$ -exponentially bounded from above.*

(2)  *$S$  verifies the  $\chi$ -growth condition if it satisfies*

$$\exists K \in \mathbb{R}_+, \exists n \in \mathbb{N}, \forall w \in X^{\geq n}, \quad \|\langle S \mid w \rangle\| \leq K \chi(w) |w|!.$$

*We denote by  $\mathbb{K}^{\chi\text{-gc}}\langle\langle X \rangle\rangle$  the set of formal power series in  $\mathbb{K}\langle\langle X \rangle\rangle$  verifying the  $\chi$ -growth condition.*

**Lemma 7.** *We have*

$$R = \sum_{w \in X^*} |w|! w \Rightarrow \langle R^{\sqcup^2} \mid w \rangle = \sum_{\substack{u, v \in X^* \\ \text{supp}(u \sqcup v) \ni w}} |u|! |v|! \leq 2^{|w|} |w|!.$$

*Proof.* One has

$$\begin{aligned}
\sum_{\substack{u, v \in X^* \\ \text{supp}(u \sqcup v) \ni w}} |u|! |v|! &= \sum_{k=0}^{|w|} \sum_{\substack{|u|=k, |v|=|w|-k \\ \text{supp}(u \sqcup v) \ni w}} k! (|w| - k)! \\
&= \sum_{k=0}^{|w|} \binom{|w|}{k} k! (|w| - k)! \\
&= \sum_{k=0}^{|w|} |w|! = (1 + |w|) |w|!.
\end{aligned}$$

By induction on  $|w|$ , one has  $1 + |w| \leq 2^{|w|}$ . The expected result follows.  $\square$

**Proposition 11.** *Let  $S_1$  and  $S_2$  verify the growth condition. Then  $S_1 + S_2$  and  $S_1 \sqcup S_2$  also verify the growth condition.*

*Proof.* The proof for  $S_1 + S_2$  is immediate.

Next, since  $\|\langle S_i | w \rangle\| \leq K_i \chi_i(w) |w|!$ , for  $i = 1$  or  $2$  and for  $w \in X^*$ , then<sup>20</sup>

$$\begin{aligned}
\langle S_1 \sqcup S_2 | w \rangle &= \sum_{\text{supp}(u \sqcup v) \ni w} \langle S_1 | u \rangle \langle S_2 | v \rangle, \\
\Rightarrow \|\langle S_1 \sqcup S_2 | w \rangle\| &\leq K_1 K_2 \sum_{\substack{u, v \in X^* \\ \text{supp}(u \sqcup v) \ni w}} (\chi_1(u) |u|!) (\chi_2(v) |v|!).
\end{aligned}$$

Let  $K = K_1 K_2$  and let  $\chi$  be a real positive function over  $X^*$  such that

$$\forall w \in X^*, \quad \chi(w) = \max\{\chi_1(u) \chi_2(v) \mid u, v \in X^* \text{ and } \text{supp}(u \sqcup v) \ni w\}.$$

With the notations in Lemma 7, we get

$$\|\langle S_1 \sqcup S_2 | w \rangle\| \leq K \chi(w) \langle R^{\sqcup 2} | w \rangle.$$

Hence,  $S_1 \sqcup S_2$  verifies the  $\chi'$ -growth condition with  $\chi'(w) = 2^{|w|} \chi(w)$ .  $\square$

**Definition 6.** ([25, 39]) *Let  $\xi$  be a real positive function defined over  $X^*$ ,  $S$  will be said  $\xi$ -exponentially continuous if it is continuous over  $\mathbb{K}^{\xi-\text{em}}\langle\langle X \rangle\rangle$ . The set of formal power series which are  $\xi$ -exponentially continuous is denoted by  $\mathbb{K}^{\xi-\text{ec}}\langle\langle X \rangle\rangle$ .*

**Lemma 8.** [25, 39] *For any real positive function  $\xi$  defined over  $X^*$ , we have  $\mathbb{K}\langle X \rangle \subset \mathbb{K}^{\xi-\text{ec}}\langle\langle X \rangle\rangle$ . Otherwise, for  $\xi = 0$ , we get  $\mathbb{K}\langle X \rangle = \mathbb{K}^{0-\text{ec}}\langle\langle X \rangle\rangle$ . Hence, any polynomial is 0-exponentially continuous.*

**Proposition 12.** ([25, 39]) *Let  $\xi, \chi$  be real positive functions over  $X^*$  and let  $P \in \mathbb{K}\langle X \rangle$ .*

<sup>20</sup> $\langle S_1 \sqcup S_2 | w \rangle$  is the coefficient of the word  $w$  in the power series  $S_1 \sqcup S_2$ .

- (1) Let  $S \in \mathbb{K}^{\xi\text{-em}}\langle\langle X \rangle\rangle$ . The right residual of  $S$  by  $P$  belongs to  $\mathbb{K}^{\xi\text{-em}}\langle\langle X \rangle\rangle$ .  
(2) Let  $R \in \mathbb{K}^{\chi\text{-gc}}\langle\langle X \rangle\rangle$ . The concatenation  $SR$  belongs to  $\mathbb{K}^{\chi\text{-gc}}\langle\langle X \rangle\rangle$ .

*Proof.* (1) Since  $S \in \mathbb{K}^{\xi\text{-em}}\langle\langle X \rangle\rangle$  then

$$\exists K \in \mathbb{R}_+, \exists n \in \mathbb{N}, \forall w \in X^{\geq n}, \quad \|\langle S \mid w \rangle\| \leq K \frac{\xi(w)}{|w|!}.$$

If  $u \in \text{supp}(P) := \{w \in X^* \mid \langle P \mid w \rangle \neq 0\}$  then, for any  $w \in X^*$ , one has  $\langle S \triangleright u \mid w \rangle = \langle S \mid uw \rangle$  and  $S \triangleright u$  belongs to  $\mathbb{K}^{\xi\text{-em}}\langle\langle X \rangle\rangle$ :

$$\exists K \in \mathbb{R}_+, \exists n \in \mathbb{N}, \forall w \in X^{\geq n}, \quad \|\langle S \triangleright u \mid w \rangle\| \leq [K\xi(u)] \frac{\xi(w)}{|w|!}.$$

It follows that  $S \triangleright P$  is  $\mathbb{K}^{\xi\text{-em}}\langle\langle X \rangle\rangle$  by taking  $K_1 = K \max_{u \in \text{supp}(P)} \xi(u)$ .

- (2) Since  $R \in \mathbb{K}^{\chi\text{-gc}}\langle\langle X \rangle\rangle$  then

$$\exists K \in \mathbb{R}_+, \exists n \in \mathbb{N}, \forall w \in X^{\geq n}, \quad \|\langle S \mid w \rangle\| \leq K \chi(w) |w|!.$$

Let  $v \in \text{supp}(P)$  such that  $v \neq \epsilon$ . Since, for any  $w \in X^*$ ,  $Rv$  belongs to  $\mathbb{K}^{\chi\text{-gc}}\langle\langle X \rangle\rangle$  and one has  $\langle Rv \mid w \rangle = \langle R \mid v \triangleleft w \rangle$ :

$$\begin{aligned} \exists K \in \mathbb{R}_+, \exists n \in \mathbb{N}, \forall w \in X^{\geq n}, \quad \|\langle R \mid v \triangleleft w \rangle\| &\leq K \chi(v \triangleleft w) (|w| - |v|)! \\ &\leq K |w| \frac{\chi(w)}{\chi(v)}. \end{aligned}$$

Note if  $v \triangleleft w = 0$  then  $\langle Rv \mid w \rangle = 0$  and the previous conclusion holds. It follows that  $RP$  is  $\mathbb{K}^{\chi\text{-gc}}\langle\langle X \rangle\rangle$  by taking  $K_2 = K \min_{v \in \text{supp}(P)} \chi(v)^{-1}$ .  $\square$

**Proposition 13.** ([25, 39]) *Two real positive morphisms over  $X^*$ ,  $\xi$  and  $\chi$  are assumed to verify the condition*

$$\sum_{x \in X} \chi(x) \xi(x) < 1.$$

*Then for any  $F \in \mathbb{K}^{\chi\text{-gc}}\langle\langle X \rangle\rangle$ ,  $F$  is continuous over  $\mathbb{K}^{\xi\text{-em}}\langle\langle X \rangle\rangle$ .*

*Proof.* If  $\xi, \chi$  verify the upper bound condition then the following power series

$$\sum_{w \in X^*} \chi(w) \xi(w) = \left( \sum_{x \in X} \chi(x) \xi(x) \right)^*$$

is well defined. If  $F \in \mathbb{K}^{\chi\text{-gc}}\langle\langle X \rangle\rangle$  and  $C \in \mathbb{K}^{\xi\text{-em}}\langle\langle X \rangle\rangle$  then there exist  $K_i \in \mathbb{R}_+$  and  $n_i \in \mathbb{N}$  such that for any  $w \in X^{\geq n_i}, i = 1, 2$ , one has

$$\|\langle F \mid w \rangle\| \leq K_1 \chi(w) |w|! \quad \text{and} \quad \|\langle C \mid w \rangle\| \leq K_2 \frac{\xi(w)}{|w|!}.$$

Hence,

$$\begin{aligned} \forall w \in X^*, |w| \geq \max\{n_1, n_2\}, \quad \|\langle F|w \rangle \langle C|w \rangle\| &\leq K_1 K_2 \chi(w) \xi(w), \\ \Rightarrow \sum_{w \in X^*} \|\langle F|w \rangle \langle C|w \rangle\| &\leq K_1 K_2 \sum_{w \in X^*} \chi(w) \xi(w) = K_1 K_2 \left( \sum_{x \in X} \chi(x) \xi(x) \right)^*. \end{aligned}$$

□

### 3.1.2 Upper bounds à la Cauchy

Let  $q_1, \dots, q_n$  be commutative indeterminates over  $\mathbb{C}$ . The algebra of formal power series (resp. polynomials) over  $\{q_1, \dots, q_n\}$  with coefficients in  $\mathbb{C}$  is denoted by  $\mathbb{C}[[q_1, \dots, q_n]]$  (resp.  $\mathbb{C}[q_1, \dots, q_n]$ ).

**Definition 7.** ([25, 39]) *Let*

$$f = \sum_{i_1, \dots, i_n \geq 0} f_{i_1, \dots, i_n} q_1^{i_1} \dots q_n^{i_n} \in \mathbb{C}[[q_1, \dots, q_n]].$$

*We set*

$$\begin{aligned} E(f) &:= \{\rho \in \mathbb{R}_+^n : \exists C_f \in \mathbb{R}_+ \text{ s.t. } \forall i_1, \dots, i_n \geq 0, |f_{i_1, \dots, i_n}| \rho_1^{i_1} \dots \rho_n^{i_n} \leq C_f\}, \\ \check{E}(f) &:= \text{the interior of } E(f) \text{ in } \mathbb{R}_+^n, \\ \text{CV}(f) &:= \{q \in \mathbb{C}^n : (|q_1|, \dots, |q_n|) \in \check{E}(f)\} : \text{the convergence domain of } f. \end{aligned}$$

*The power series  $f$  is said to be convergent if  $\text{CV}(f) \neq \emptyset$ . Let  $\mathcal{U}$  be an open domain in  $\mathbb{C}^n$  and let  $q \in \mathbb{C}^n$ . The power series  $f$  is said to be convergent on  $q$  (resp. over  $\mathcal{U}$ ) if  $q \in \text{CV}(f)$  (resp.  $\mathcal{U} \subset \text{CV}(f)$ ). We set*

$$\mathbb{C}^{\text{cv}}[[q_1, \dots, q_n]] = \{f \in \mathbb{C}[[q_1, \dots, q_n]] : \text{CV}(f) \neq \emptyset\}.$$

*Let  $q \in \text{CV}(f)$ . There exist the constants  $C_f, \rho$  and  $\bar{\rho}$  such that*

$$|q_1| < \bar{\rho} < \rho, \dots, |q_n| < \bar{\rho} < \rho \quad \text{and} \quad |f_{i_1, \dots, i_n}| \rho_1^{i_1} \dots \rho_n^{i_n} \leq C_f,$$

*for  $i_1, \dots, i_n \geq 0$ . The convergence modulus of  $f$  at  $q$  is  $(C_f, \rho, \bar{\rho})$ .*

Suppose that  $\text{CV}(f) \neq \emptyset$  and let  $q \in \text{CV}(f)$ . If  $(C_f, \rho, \bar{\rho})$  is a convergence modulus of  $f$  at  $q$  then  $|f_{i_1, \dots, i_n} q_1^{i_1} \dots q_n^{i_n}| \leq C_f (\bar{\rho}_1 / \rho_1)^{i_1} \dots (\bar{\rho}_n / \rho_n)^{i_n}$ . Hence, at  $q$ , the power series  $f$  is majored termwise by

$$C_f \prod_{k=0}^m \left(1 - \frac{\bar{\rho}_k}{\rho_k}\right)^{-1}. \quad (83)$$

Hence,  $f$  is uniformly absolutely convergent in  $\{q \in \mathbb{C}^n : |q_1| < \bar{\rho}, \dots, |q_n| < \bar{\rho}\}$  which is an open domain in  $\mathbb{C}^n$ . Thus,  $\text{CV}(f)$  is an open domain in  $\mathbb{C}^n$ . Since the partial derivation  $D_1^{j_1} \dots D_n^{j_n} f$  is estimated by

$$\|D_1^{j_1} \dots D_n^{j_n} f\| \leq C_f \frac{\partial^{j_1 + \dots + j_n}}{\partial \bar{\rho}^{j_1 + \dots + j_n}} \prod_{k=0}^m \left(1 - \frac{\bar{\rho}_k}{\rho_k}\right)^{-1}. \quad (84)$$

**Proposition 14.** ([25]) *We have  $\text{CV}(f) \subset \text{CV}(D_1^{j_1} \dots D_n^{j_n} f)$ .*

Let  $f \in \mathbb{C}^{\text{cv}}[[q_1, \dots, q_n]]$ . Let  $\{A_i\}_{i=0,1}$  be a polysystem defined as follows

$$A_i(q) = \sum_{j=1}^n A_i^j(q) \frac{\partial}{\partial q_j}, \quad (85)$$

where for any  $j = 1, \dots, n$ ,  $A_i^j(q) \in \mathbb{C}^{\text{cv}}[[q_1, \dots, q_n]]$ .

**Lemma 9.** ([22]) *For  $i = 0, 1$  and  $j = 1, \dots, n$ , one has  $A_i \circ q_j = A_i^j(q)$ . Thus,*

$$\forall i = 0, 1, \quad A_i(q) = \sum_{j=1}^n (A_i \circ q_j) \frac{\partial}{\partial q_j}.$$

Let  $(\rho, \bar{\rho}, C_f), \{(\rho, \bar{\rho}, C_i)\}_{i=0,1}$  be respectively the convergence modulus at

$$q \in \text{CV}(f) \bigcap_{\substack{i=0,1 \\ j=1, \dots, n}} \text{CV}(A_i^j) \quad (86)$$

of  $f$  and  $\{A_i^j\}_{j=1, \dots, n}$ . Let us consider the following monoid morphisms

$$\mathcal{A}(\epsilon) = \text{identity} \quad \text{and} \quad C(\epsilon) = 1, \quad (87)$$

$$\forall w = vx_i, x_i \in X, v \in X^*, \quad \mathcal{A}(w) = \mathcal{A}(v)A_i \quad \text{and} \quad C(w) = C(v)C_i. \quad (88)$$

**Lemma 10.** ([20]) *For any word  $w$ ,  $\mathcal{A}(w)$  is continuous over  $\mathbb{C}^{\text{cv}}[[q_1, \dots, q_n]]$  and, for any  $f, g \in \mathbb{C}^{\text{cv}}[[q_1, \dots, q_n]]$ , one has*

$$\mathcal{A}(w) \circ (fg) = \sum_{u, v \in X^*} \langle u \sqcup v \mid w \rangle (\mathcal{A}(u) \circ f) (\mathcal{A}(v) \circ g).$$

These notations are extended, by linearity, to  $\mathbb{K}\langle X \rangle$  and we will denote  $\mathcal{A}(w) \circ f|_q$  the evaluation of  $\mathcal{A}(w) \circ f$  at  $q$ .

**Definition 8.** ([20]) *Let  $f \in \mathbb{C}^{\text{cv}}[[q_1, \dots, q_n]]$ . The generating series of the polysystem  $\{A_i\}_{i=0,1}$  and of the observation  $f$  is given by*

$$\sigma f := \sum_{w \in X^*} \mathcal{A}(w) \circ f w \in \mathbb{C}^{\text{cv}}[[q_1, \dots, q_n]]\langle\langle X \rangle\rangle.$$

*Then the following generating series is called Fliess generating series of the polysystem  $\{A_i\}_{i=0,1}$  and of the observation  $f$  at  $q$ :*

$$\sigma f|_q := \sum_{w \in X^*} \mathcal{A}(w) \circ f|_q w \in \mathbb{C}\langle\langle X \rangle\rangle.$$

**Lemma 11.** ([20]) *Let  $\{A_i\}_{i=0,1}$  be a polysystem. Then, the map*

$$\sigma : (\mathbb{C}^{\text{cv}}[[q_1, \dots, q_n]], \cdot) \longrightarrow (\mathbb{C}^{\text{cv}}[[q_1, \dots, q_n]]\langle\langle X \rangle\rangle, \sqcup),$$

*is an algebra morphism, i.e. for  $f, g \in \mathbb{C}^{\text{cv}}[[q_1, \dots, q_n]]$  and  $\mu, \nu \in \mathbb{C}$ , one has:*

$$\sigma(\nu f + \mu h) = \nu \sigma f + \mu \sigma g \quad \text{and} \quad \sigma(fg) = \sigma f \sqcup \sigma g.$$

**Lemma 12.** ([22]) *Let  $\{A_i\}_{i=0,1}$  be a polysystem and  $f \in \mathbb{C}^{\text{cv}}[[q_1, \dots, q_n]]$ . Then*

$$\begin{aligned} \forall x_i \in X, \quad \sigma(A_i \circ f) = x_i \triangleleft \sigma f &\in \mathbb{C}^{\text{cv}}[[q_1, \dots, q_n]]\langle\langle X \rangle\rangle \\ \forall w \in X^*, \quad \sigma(\mathcal{A}(w) \circ f) = w \triangleleft \sigma f &\in \mathbb{C}^{\text{cv}}[[q_1, \dots, q_n]]\langle\langle X \rangle\rangle. \end{aligned}$$

**Lemma 13.** ([25]) *Let  $\tau = \min_{1 \leq k \leq n} \rho_k$  and  $r = \max_{1 \leq k \leq n} \bar{\rho}_k / \rho_k$ . We have*

$$\begin{aligned} \|\mathcal{A}(w) \circ f\| &\leq C_f \frac{(n+1)}{(1-r)^n} \frac{C(w) |w|!}{\binom{n+|w|-1}{|w|}} \left[ \frac{n}{\tau(1-r)^{n+1}} \right]^{|w|} \\ &\leq C_f \frac{(n+1)}{(1-r)^n} C(w) \left[ \frac{n}{\tau(1-r)^{n+1}} \right]^{|w|} |w|!. \end{aligned}$$

**Theorem 8.** ([25]) *Let  $K = C_f(n+1)(1-r)^{-n}$  and let  $\chi$  be the real positive function defined over  $X^*$  by*

$$\forall i = 0, 1, \quad \chi(x_i) = \frac{C_i n}{\tau(1-r)^{(n+1)}}.$$

*Then the generating series  $\sigma f$  of the polysystem  $\{A_i\}_{i=0,1}$  and of the observation  $f$  satisfies the  $\chi$ -growth condition.*

It is the same for the Fliess generating series  $\sigma f|_q$  of the polysystem  $\{A_i\}_{i=0,1}$  and of the observation  $f$  at  $q$ .

## 3.2 Polysystem and nonlinear differential equation

### 3.2.1 Nonlinear differential equation (with three singularities)

Let us consider the singular inputs<sup>21</sup>  $u_0(z) := z^{-1}$  and  $u_1(z) := (1-z)^{-1}$ , and the following nonlinear dynamical system

$$\begin{cases} y(z) &= f(q(z)), \\ \dot{q}(z) &= A_0(q) u_0(z) + A_1(q) u_1(z), \\ q(z_0) &= q_0, \end{cases} \quad (89)$$

where the state  $q = (q_1, \dots, q_n)$  belongs to the complex analytic manifold of dimension  $n$ ,  $q_0$  is the initial state, the observation  $f$  belongs to  $\mathbb{C}^{\text{cv}}[[q_1, \dots, q_n]]$  and  $\{A_i\}_{i=0,1}$  is the polysystem defined on (85).

**Definition 9.** ([27]) *The following power series is called transport operator of the polysystem  $\{A_i\}_{i=0,1}$  and of the observation  $f$*

$$\mathcal{T} := \sum_{w \in X^*} \alpha_{z_0}^z(w) \mathcal{A}(w).$$

<sup>21</sup>These singular inputs are not included in the studies of Fliess motivated, in particular, by the renormalization of  $y(z)$  at  $+\infty$  [20, 22].

By the factorization of the monoid by Lyndon words, we have [27]

$$\mathcal{T} = (\alpha_{z_0}^z \otimes \mathcal{A}) \left( \sum_{w \in X^*} w \otimes w \right) = \prod_{l \in \text{Lyn} X} \exp[\alpha_{z_0}^z(S_l) \mathcal{A}(P_l)]. \quad (90)$$

The Chen generating series along the path  $z_0 \rightsquigarrow z$ , associated to  $\omega_0, \omega_1$  is

$$S_{z_0 \rightsquigarrow z} := \sum_{w \in X^*} \langle S | w \rangle w \quad \text{with} \quad \langle S | w \rangle = \alpha_{z_0}^z(w) \quad (91)$$

which solves the differential equation (72) with the initial condition  $S_{z_0 \rightsquigarrow z_0} = 1$ . Thus,  $S_{z_0 \rightsquigarrow z}$  and  $L(z)L(z_0)^{-1}$  satisfy the same differential equation taking the same value at  $z_0$  and  $S_{z_0 \rightsquigarrow z} = L(z)L(z_0)^{-1}$ .

Any Chen generating series  $S_{z_0 \rightsquigarrow z}$  is group like [46] and depends only on the homotopy class of  $z_0 \rightsquigarrow z$  [9]. The product of  $S_{z_1 \rightsquigarrow z_2}$  and  $S_{z_0 \rightsquigarrow z_1}$  is  $S_{z_0 \rightsquigarrow z_2} = S_{z_1 \rightsquigarrow z_2} S_{z_0 \rightsquigarrow z_1}$ . Let  $\varepsilon \in ]0, 1[$  and  $z_i = \varepsilon \exp(i\beta_i)$ , for  $i = 0$  or  $1$ . We set  $\beta = \beta_1 - \beta_0$ . Let  $\Gamma_0(\varepsilon, \beta_0)$  (resp.  $\Gamma_1(\varepsilon, \beta_1)$ ) be the path turning around 0 (resp. 1) in the positive direction from  $z_0$  to  $z_1$ . By induction on the length of  $w$ , one has

$$|\langle S_{\Gamma_i(\varepsilon, \beta)} | w \rangle| = (2\varepsilon)^{|w|_{x_i}} \frac{\beta^{|w|}}{|w|!}, \quad (92)$$

where  $|w|$  denotes the length of  $w$  and  $|w|_{x_i}$  denotes the number of occurrences of letter  $x_i$  in  $w$ , for  $i = 0$  or  $1$ . For  $\varepsilon$  tends to  $0^+$ , these estimations yield  $S_{\Gamma_i(\varepsilon, \beta)} = e^{i\beta x_i} + o(\varepsilon)$ . In particular, if  $\Gamma_0(\varepsilon)$  (resp.  $\Gamma_1(\varepsilon)$ ) is a circular path of radius  $\varepsilon$  turning around 0 (resp. 1) in the positive direction, starting at  $z = \varepsilon$  (resp.  $1 - \varepsilon$ ), then, by the noncommutative residue theorem [35, 32], we get

$$S_{\Gamma_0(\varepsilon)} = e^{2i\pi x_0} + o(\varepsilon) \quad \text{and} \quad S_{\Gamma_1(\varepsilon)} = e^{-2i\pi x_1} + o(\varepsilon). \quad (93)$$

Finally, the asymptotic behaviors of  $L$  on (73) give [32, 35]

$$S_{\varepsilon \rightsquigarrow 1-\varepsilon} \underset{\varepsilon \rightarrow 0^+}{\sim} e^{-x_1 \log \varepsilon} Z_{\sqcup} e^{-x_0 \log \varepsilon}. \quad (94)$$

In other terms,  $Z_{\sqcup}$  is the regularized Chen generating series  $S_{\varepsilon \rightsquigarrow 1-\varepsilon}$  of differential forms  $\omega_0$  and  $\omega_1$ :  $Z_{\sqcup}$  is the noncommutative generating series of the finite parts of the coefficients of the Chen generating series  $e^{x_1 \log \varepsilon} S_{\varepsilon \rightsquigarrow 1-\varepsilon} e^{x_0 \log \varepsilon}$ , *i.e.* the concatenation of  $e^{x_0 \log \varepsilon}$  and then  $S_{\varepsilon \rightsquigarrow 1-\varepsilon}$  and finally,  $e^{x_1 \log \varepsilon}$ .

### 3.2.2 Asymptotic behavior of the successive differentiation of solution via extended Fliess fundamental formula

The Fliess' fundamental formula [20] can be then extended as follows

**Theorem 9.** ([39]) *We have*

$$y(z) = \mathcal{T} \circ f|_{q_0} = \sum_{w \in X^*} \langle S_{z_0 \rightsquigarrow z} | w \rangle \langle \mathcal{A}(w) \circ f|_{q_0} | w \rangle = \langle \sigma f|_{q_0} \parallel S_{z_0 \rightsquigarrow z} \rangle.$$



By the factorization of the Lie exponential series  $L$ , the expansions of the output  $y$  of nonlinear dynamical system with singular inputs follow

**Corollary 2.**

$$\begin{aligned}
y(z) &= \sum_{w \in X^*} g_w(z) \mathcal{A}(w) \circ f|_{q_0} \\
&= \sum_{k \geq 0} \sum_{n_1, \dots, n_k \geq 0} g_{x_0^{n_1} x_1 \dots x_0^{n_k} x_1}(z) \text{ad}_{A_0}^{n_1} A_1 \dots \text{ad}_{A_0}^{n_k} A_1 e^{\log z A_0} \circ f|_{q_0} \\
&= \prod_{l \in \mathcal{L}y_n X} \exp\left(g_{S_l}(z) \mathcal{A}(P_l) \circ f|_{q_0}\right) \\
&= \exp\left(\sum_{w \in X^*} g_w(z) \mathcal{A}(\pi_1(w)) \circ f|_{q_0}\right),
\end{aligned}$$

where, for any word  $w$  in  $X^*$ ,  $g_w$  belongs to the polylogarithm algebra.

Since  $S_{z_0 \rightsquigarrow z} = L(z)L(z_0)^{-1}$  and since  $\sigma f|_{q_0}$  and  $L(z_0)^{-1}$  are invariant by  $\partial_z = d/dz$  and by  $\theta_0 = zd/dz$  then we obtain the  $n$ -order differentiation of  $y$  :

$$\partial_z^n y(z) = \langle \sigma f|_{q_0} \parallel \partial^n S_{z_0 \rightsquigarrow z} \rangle = \langle \sigma f|_{q_0} \parallel \partial_z^n L(z)L(z_0)^{-1} \rangle \quad (95)$$

and the  $n$ -order differentiation of  $y$  with respect to  $\theta_0$  :

$$\theta_0^n y(z) = \langle \sigma f|_{q_0} \parallel \theta_0^n S_{z_0 \rightsquigarrow z} \rangle = \langle \sigma f|_{q_0} \parallel \theta_0^n L(z)L(z_0)^{-1} \rangle. \quad (96)$$

With the notations of Proposition 5, we get respectively

$$\partial_z^n y(z) = \langle \sigma f|_{q_0} \parallel [D_n(z)L(z)]L(z_0)^{-1} \rangle = \langle \sigma f|_{q_0} \triangleright D_n(z) \parallel L(z)L(z_0)^{-1} \rangle, \quad (97)$$

$$\theta_0^n y(z) = \langle \sigma f|_{q_0} \parallel [E_n(z)L(z)]L(z_0)^{-1} \rangle = \langle \sigma f|_{q_0} \triangleright E_n(z) \parallel L(z)L(z_0)^{-1} \rangle. \quad (98)$$

For  $z_0 = \varepsilon \rightarrow 0^+$ , the asymptotic behavior and the renormalization at  $z = 1$  of  $\partial_z^n y(z)$  and  $\theta_0^n y(z)$  (or the asymptotic expansion and the renormalization of its Taylor coefficients at  $+\infty$ ) are deduced from (94) and extend a little bit the results of [39] as follows

**Corollary 3.** *For any integer  $n$ , we have respectively<sup>22</sup>*

<sup>22</sup>We overget, by Note 18, the  $n$ -order differentiation of  $y$  w.r.t.  $\theta_1$  :

$$\theta_1^n y(z) = \langle \sigma f|_{q_0} \parallel \theta_1^n S_{z_0 \rightsquigarrow z} \rangle = \langle \sigma f|_{q_0} \parallel \theta_1^n L(z)L(z_0)^{-1} \rangle.$$

Hence,

$$\theta_1^n y(z) = \langle \sigma f|_{q_0} \parallel [D_n(z) - E_n(z)]L(z)L(z_0)^{-1} \rangle = \langle \sigma f|_{q_0} \triangleright [D_n(z) - E_n(z)] \parallel L(z)L(z_0)^{-1} \rangle$$

and then

$$\theta_1^n y(1) \underset{\varepsilon \rightarrow 0^+}{\widetilde{}} \sum_{w \in X^*} \langle \mathcal{A}(w) \circ f|_{q_0} \mid w \rangle \langle [D_n(1 - \varepsilon) - E_n(1 - \varepsilon)] e^{-x_1 \log \varepsilon} Z_{\perp\perp} e^{-x_0 \log \varepsilon} \mid w \rangle.$$

The actions of  $\theta_0 = u_0(z)^{-1}d/dz$  and  $\theta_1 = u_1(z)^{-1}d/dz$  over  $y(z)$  are equivalent to those of the residuals respectively by  $x_0$  and  $x_1$  over  $\sigma f|_{q_0}$  and correspond to *functional* differentiations [21] while  $\partial_z = d/dz$  is the ordinary differentiation and is equivalent to the residual by  $x_0 + x_1$ .

$$\begin{aligned}\partial_z^n y(1) &\underset{\varepsilon \rightarrow 0^+}{\widetilde{}} \sum_{w \in X^*} \langle \mathcal{A}(w) \circ f|_{q_0} \mid w \rangle \langle D_n(1 - \varepsilon) e^{-x_1 \log \varepsilon} Z_{\perp\perp} e^{-x_0 \log \varepsilon} \mid w \rangle, \\ \theta_0^n y(1) &\underset{\varepsilon \rightarrow 0^+}{\widetilde{}} \sum_{w \in X^*} \langle \mathcal{A}(w) \circ f|_{q_0} \mid w \rangle \langle E_n(1 - \varepsilon) e^{-x_1 \log \varepsilon} Z_{\perp\perp} e^{-x_0 \log \varepsilon} \mid w \rangle.\end{aligned}$$

**Corollary 4.** *The  $n$ -order differentiation of the output  $y$  of the system (89) is a  $\mathcal{C}$ -combination of the elements  $g$  belonging to the polylogarithm algebra.*

*Moreover, if the ordinary Taylor expansions of  $\partial_z^n y$  and  $\theta_0^n y$  exist :*

$$\partial_z^n y(z) = \sum_{k \geq 0} d_k z^k \quad \text{and} \quad \theta_0^n y(z) = \sum_{k \geq 0} t_k z^k$$

*then the coefficients of these expansions belong to the algebra of harmonic sums and there exist algorithmically computable coefficients  $a_i, a'_i \in \mathbb{Z}, b_i, b'_i \in \mathbb{N}$  and  $c_i, c'_i \in \mathcal{Z}[\gamma]$  such that*

$$d_k \underset{k \rightarrow \infty}{\widetilde{}} \sum_{i \geq 0} c_i k^{a_i} \log^{b_i} k \quad \text{and} \quad t_k \underset{k \rightarrow \infty}{\widetilde{}} \sum_{i \geq 0} c'_i k^{a'_i} \log^{b'_i} k.$$

### 3.3 Differential realization

#### 3.3.1 Differential realization

**Definition 10.** *The Lie rank of a formal power series  $S \in \mathbb{K}\langle\langle X \rangle\rangle$  is the dimension of the vector space generated by*

$$\{S \triangleright \Pi \mid \Pi \in \mathcal{L}ie_{\mathbb{K}}\langle X \rangle\}, \quad \text{or respectively by} \quad \{\Pi \triangleleft S \mid \Pi \in \mathcal{L}ie_{\mathbb{K}}\langle X \rangle\}.$$

**Example 10.** *Let  $P = x_1 x_0 x_1 + x_0 x_1 x_0 x_1$  be a polynomial of degree 4 over  $X = \{x_0, x_1\}$ . A basis up to degree 4 of the Lie algebra  $\mathcal{L}ie_{\mathbb{K}}\langle X \rangle$  is following (c.f. Example 4)*

$$\{P_{x_0}, P_{x_1}, P_{x_0 x_1}, P_{x_0^2 x_1}, P_{x_0 x_1^2}, P_{x_0^3 x_1}, P_{x_0 x_1^3}, P_{x_0^2 x_1^2}\}.$$

*The Lie-Hankel matrix of  $P$  is following*

$$\begin{array}{ccccc} & 1_{X^*} & x_1 & x_0 x_1 & x_1 x_0 x_1 \\ P_{x_0} & 0 & 0 & 0 & 1 \\ P_{x_1} & 0 & 0 & 1 & 0 \\ P_{x_0 x_1} & 0 & -1 & 1 & 0 \\ P_{x_0^2 x_1} & 0 & -2 & 0 & 0 \\ P_{x_0 x_1^2} & -2 & 0 & 0 & 0 \\ P_{x_0^2 x_1^2} & -2 & 0 & 0 & 0\end{array}$$

*and its Lie-Hankel rank of  $P$  is then 4.*

**Definition 11.** Let  $S \in \mathbb{K}\langle\langle X \rangle\rangle$  and let us put

$$\begin{aligned}\text{Ann}(S) &:= \{\Pi \in \mathcal{L}ie_{\mathbb{K}}\langle X \rangle \mid S \triangleright \Pi = 0\}, \\ \text{Ann}^{\perp}(S) &:= \{Q \in (\mathbb{K}\langle\langle X \rangle\rangle, \sqcup) \mid Q \triangleright \text{Ann}(S) = 0\}.\end{aligned}$$

It is immediate that  $\text{Ann}^{\perp}(S) \ni S$  and it follows that (see [22, 48]).

**Lemma 14.** Let  $S \in \mathbb{K}\langle\langle X \rangle\rangle$ . If  $S$  is of finite Lie rank,  $d$ , then the dimension of  $\text{Ann}^{\perp}(S)$  equals  $d$ .

By Lemma 3, the residuals are derivations for shuffle product. Then,

**Lemma 15.** Let  $S \in \mathbb{K}\langle\langle X \rangle\rangle$ . Then:

- (1) For any  $Q_1$  and  $Q_2 \in \text{Ann}^{\perp}(S)$ , one has  $Q_1 \sqcup Q_2 \in \text{Ann}^{\perp}(S)$ .
- (2) For any  $P \in \mathbb{K}\langle X \rangle$  and  $Q_1 \in \text{Ann}^{\perp}(S)$ , one has  $P \triangleleft Q_1 \in \text{Ann}^{\perp}(S)$ .

**Definition 12.** ([22]) The formal power series  $S \in \mathbb{K}\langle\langle X \rangle\rangle$  is differentially produced if there exist

- an integer  $d$ ,
- a power series  $f \in \mathbb{K}[[\bar{q}_1, \dots, \bar{q}_d]]$ ,
- a homomorphism  $\mathcal{A}$  from  $X^*$  maps to the algebra of differential operators generated by

$$\mathcal{A}(x_i) = \sum_{j=1}^d A_i^j(\bar{q}_1, \dots, \bar{q}_d) \frac{\partial}{\partial \bar{q}_j},$$

where, for  $j = 1, \dots, d$ ,  $A_i^j(\bar{q}_1, \dots, \bar{q}_d)$  belongs to  $\mathbb{K}[[\bar{q}_1, \dots, \bar{q}_d]]$  such that

$$\forall w \in X^*, \quad \langle S \mid w \rangle = \mathcal{A}(w) \circ f|_0.$$

The couple  $(\mathcal{A}, f)$  is called the differential representation of  $S$  of dimension  $d$ .

**Proposition 15.** ([48]) Let  $S \in \mathbb{K}\langle\langle X \rangle\rangle$ . If  $S$  is differentially produced then it verifies the growth condition and its Lie rank is finite.

*Proof.* Let  $(\mathcal{A}, f)$  be a differential representation of  $S$  of dimension  $d$ . Then, by the notations of Definition 8, we get

$$\sigma f|_0 = S = \sum_{w \in X^*} (\mathcal{A}(w) \circ f)|_0 w.$$

For any  $j = 1, \dots, d$ , we put

$$T_j = \sum_{w \in X^*} \frac{\partial(\mathcal{A}(w) \circ f)}{\partial \bar{q}_j} w.$$

Firstly, by Theorem 8, the generating series  $\sigma f$  verifies the growth condition. Secondly, for any  $\Pi \in \mathcal{L}ie_{\mathbb{K}}\langle X \rangle$  and for any  $w \in X^*$ , one has

$$\langle \sigma f \triangleright \Pi \mid w \rangle = \langle \sigma f \mid \Pi w \rangle = \mathcal{A}(\Pi w) \circ f = \mathcal{A}(\Pi) \circ (\mathcal{A}(w) \circ f).$$

Since  $\mathcal{A}(\Pi)$  is a derivation over  $\mathbb{K}[\bar{q}_1, \dots, \bar{q}_d]$ :

$$\begin{aligned} \mathcal{A}(\Pi) &= \sum_{j=1}^d (\mathcal{A}(\Pi) \circ \bar{q}_j) \frac{\partial}{\partial \bar{q}_j}, \\ \Rightarrow \mathcal{A}(\Pi) \circ (\mathcal{A}(w) \circ f) &= \sum_{j=1}^d (\mathcal{A}(\Pi) \circ \bar{q}_j) \frac{\partial (\mathcal{A}(w) \circ f)}{\partial \bar{q}_j} \end{aligned}$$

then we deduce that

$$\begin{aligned} \forall w \in X^*, \quad \langle \sigma f \triangleright \Pi \mid w \rangle &= \sum_{j=1}^d (\mathcal{A}(\Pi) \circ \bar{q}_j) \langle T_j \mid w \rangle, \\ \Leftrightarrow \sigma f \triangleright \Pi &= \sum_{j=1}^d (\mathcal{A}(\Pi) \circ \bar{q}_j) T_j. \end{aligned}$$

That means  $\sigma f \triangleright \Pi$  is  $\mathbb{K}$ -linear combination of  $\{T_j\}_{j=1, \dots, d}$  and the dimension of the vector space  $\text{span}\{\sigma f \triangleright \Pi \mid \Pi \in \mathcal{L}ie_{\mathbb{K}}\langle X \rangle\}$  is less than or equal to  $d$ .  $\square$

### 3.3.2 Fliess' local realization theorem

**Proposition 16.** ([48]) *Let  $S \in \mathbb{K}\langle\langle X \rangle\rangle$  be such that its Lie rank equals  $d$ . Then there exists a basis  $S_1, \dots, S_d \in \mathbb{K}\langle\langle X \rangle\rangle$  of  $(\text{Ann}^\perp(S), \sqcup) \cong (\mathbb{K}[S_1, \dots, S_d], \sqcup)$  such that the  $S_i$ 's are proper and for any  $R \in \text{Ann}^\perp(S)$ , one has*

$$R = \sum_{i_1, \dots, i_d \geq 0} \frac{r_{i_1, \dots, i_d}}{i_1! \dots i_d!} S_1^{\sqcup i_1} \sqcup \dots \sqcup S_d^{\sqcup i_d},$$

where the coefficients  $\{r_{i_1, \dots, i_d}\}_{i_1, \dots, i_d \geq 0}$  belong to  $\mathbb{K}$  and  $r_{0, \dots, 0} = \langle R \mid 1_{X^*} \rangle$ .

*Proof.* By Lemma 14, such a basis exists. More precisely, since the Lie rank of  $S$  is  $d$  then there exist  $P_1, \dots, P_d \in \mathcal{L}ie_{\mathbb{K}}\langle X \rangle$  such that  $S \triangleright P_1, \dots, S \triangleright P_d \in (\mathbb{K}\langle\langle X \rangle\rangle, \sqcup)$  are  $\mathbb{K}$ -linearly independent. By duality, there exist  $S_1, \dots, S_d \in (\mathbb{K}\langle\langle X \rangle\rangle, \sqcup)$  such that

$$\forall i, j = 1, \dots, d, \quad \langle S_i \mid P_j \rangle = \delta_{i,j}, \quad \text{and} \quad R = \prod_{i=1}^d \exp(S_i P_i).$$

Expanding this product, one obtains, via PBW theorem, the expected expression for the coefficients  $\{r_{i_1, \dots, i_d} = \langle R \mid P_1^{i_1} \dots P_d^{i_d} \rangle\}_{i_1, \dots, i_d \geq 0}$ . Hence,  $(\text{Ann}^\perp(S), \sqcup)$  is generated by  $S_1, \dots, S_d$ .  $\square$

With the notations of Proposition 16, one has respectively.

**Corollary 5.** *If  $S \in \mathbb{K}[S_1, \dots, S_d]$  then, for any  $i = 0, 1$  and for any  $j = 1, \dots, d$ , one has  $x_i \triangleleft S \in \text{Ann}^\perp(S) = \mathbb{K}[S_1, \dots, S_d]$ .*

**Corollary 6.** *The power series  $S$  verifies the growth condition if and only if, for any  $i = 1, \dots, d$ ,  $S_i$  also verifies the growth condition.*

*Proof.* Assume there exists  $j \in [1, \dots, d]$  such that  $S_j$  does not verify the growth condition. Since  $S \in \text{Ann}^\perp(S)$  then using the decomposition of  $S$  on  $S_1, \dots, S_d$ , one obtains a contradiction with the fact that  $S$  verifies the growth condition.

Conversely, using Proposition 11, we get the expected results.  $\square$

**Theorem 10.** ([22]) *The formal power series  $S \in \mathbb{K}\langle\langle X \rangle\rangle$  is differentially produced if and only if its Lie rank is finite and if it verifies the  $\chi$ -growth condition.*

*Proof.* By Proposition 15, one gets a direct proof.

Conversely, since the Lie rank of  $S$  equals  $d$  then by Proposition 16, by putting  $\sigma f|_0 = S$  and, for any  $j = 1, \dots, d$ ,  $\sigma \bar{q}_i = S_i$ ,

(1) we choose the observation  $f$  as follows

$$f(\bar{q}_1, \dots, \bar{q}_d) = \sum_{i_1, \dots, i_d \geq 0} \frac{r_{i_1, \dots, i_d}}{i_1! \dots i_d!} \bar{q}_1^{i_1} \dots \bar{q}_d^{i_d} \in \mathbb{K}[\bar{q}_1, \dots, \bar{q}_d]$$

such that

$$\sigma f|_0(\bar{q}_1, \dots, \bar{q}_d) = \sum_{i_1, \dots, i_d \geq 0} \frac{r_{i_1, \dots, i_d}}{i_1! \dots i_d!} (\sigma \bar{q}_1)^{\sqcup i_1} \sqcup \dots \sqcup (\sigma \bar{q}_d)^{\sqcup i_d},$$

(2) it follows that, for  $i = 0, 1$  and for  $j = 1, \dots, d$ , the residual  $x_i \triangleleft \sigma \bar{q}_j$  belongs to  $\text{Ann}^\perp(\sigma f|_0)$  (see also Lemma 15),

(3) since  $\sigma f$  verifies the  $\chi$ -growth condition then, by Corollary 6, the generating series  $\sigma \bar{q}_j$  and  $x_i \triangleleft \sigma \bar{q}_j$  (for  $i = 0, 1$  and for  $j = 1, \dots, d$ ) verify also the growth condition. We then take (see Lemma 12)

$$\forall i = 0, 1, \quad \forall j = 1, \dots, d, \quad \sigma A_j^i(\bar{q}_1, \dots, \bar{q}_d) = x_i \triangleleft \sigma \bar{q}_j,$$

by expressing  $\sigma A_j^i$  on the basis  $\{\sigma \bar{q}_i\}_{i=1, \dots, d}$  of  $\text{Ann}^\perp(\sigma f|_0)$ ,

(4) the homomorphism  $\mathcal{A}$  is then determined as follows

$$\forall i = 0, 1, \quad \mathcal{A}(x_i) = \sum_{j=0}^d A_j^i(\bar{q}_1, \dots, \bar{q}_d) \frac{\partial}{\partial \bar{q}_j},$$

where, by Lemma 9, one has  $A_j^i(\bar{q}_1, \dots, \bar{q}_d) = \mathcal{A}(x_i) \circ \bar{q}_j$ .

Thus,  $(\mathcal{A}, f)$  provides a differential representation<sup>23</sup> of dimension  $d$  of  $S$ .  $\square$

<sup>23</sup>In [22, 48], the reader can find the discussion on the *minimal* differential representation.

Moreover, one also has the following

**Theorem 11.** ([22]) *Let  $S \in \mathbb{K}\langle\langle X \rangle\rangle$  be a differentially produced formal power series. Let  $(\mathcal{A}, f)$  and  $(\mathcal{A}', f')$  be two differential representations of dimension  $n$  of  $S$ . There exist a continuous and convergent automorphism  $h$  of  $\mathbb{K}$  such that*

$$\forall w \in X^*, \forall g \in \mathbb{K}, \quad h(\mathcal{A}(w) \circ g) = \mathcal{A}'(w) \circ (h(g)) \quad \text{and} \quad f' = h(f).$$

Since any rational power series verifies the growth condition and its Lie rank is less than or equal to its Hankel rank which is finite [22] then

**Corollary 7.** *Any rational power series and any polynomial over  $X$  with coefficients in  $\mathbb{K}$  are differentially produced.*

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