

DRINFELD ASSOCIATORS, BRAID GROUPS AND EXPLICIT SOLUTIONS OF THE KASHIWARA-VERGNE EQUATIONS

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ABSTRACT. The Kashiwara-Vergne (KV) conjecture states the existence of solutions of a pair of equations related with the Campbell-Baker-Hausdorff series. It was solved by Meinrenken and the first author over \mathbb{R} , and in a formal version, by the first and last authors over a field of characteristic 0. In this paper, we give a simple and explicit formula for a map from the set of Drinfeld associators to the set of solutions of the formal KV equations. Both sets are torsors under the actions of pronipotent groups, and we show that this map is a morphism of torsors. When specialized to the KZ associator, our construction yields a solution over \mathbb{R} of the original KV conjecture.

INTRODUCTION

In [KV], M. Kashiwara and M. Vergne formulated a conjecture on the form of the Campbell-Baker-Hausdorff (CBH) series. This conjecture triggered the work of several authors (for a review see [T2]). In particular, Kashiwara-Vergne settled it for solvable Lie algebras ([KV]), Rouvière gave a proof for $sl_2(\mathbb{R})$, and Vergne ([V]) and Alekseev-Meinrenken ([AM1]) proved it for quadratic Lie algebras. All these constructions lead to explicit rational formulas for solutions of the KV conjecture. The general case was settled in the positive by Alekseev-Meinrenken ([AM2]) using Kontsevich's deformation quantization theory and results in [T1]. The corresponding solution is defined over \mathbb{R} , and expresses as an infinite series where coefficients are combinations of Kontsevich integrals on configuration spaces and integrals over simplices. The values of most of these coefficients remain unknown.

Later, the first and last authors gave another proof ([AT]), based on Drinfeld's theory of associators. In that paper, the Kashiwara-Vergne (KV) conjecture was reformulated as the problem of constructing special automorphisms of the free Lie algebra with two generators with coboundary Jacobian (see Section 2); the authors also showed that each associator gives rise to an affine line of such automorphisms. The solution is defined as a nonabelian cochain with coboundary equal to the associator. Such a construction is inspired by the theory of quantization of Lie bialgebras, and the existence problem is solved by showing that obstructions vanish in all degrees.

The purpose of the present work is to give a direct construction of the map $M_1(\mathfrak{k}) \rightarrow \text{SolKV}(\mathfrak{k})$, $\Phi \mapsto \mu_\Phi$ from associators to solutions of the KV equations (we work over a field \mathfrak{k} of characteristic 0). Namely, for $\Phi \in M_1(\mathfrak{k})$, μ_Φ is the automorphism of the topologically free Lie algebra generated by x, y given by

$$(1) \quad \mu_\Phi : x \mapsto \Phi(x, -x-y)x\Phi(x, -x-y)^{-1}, \quad y \mapsto e^{-(x+y)/2}\Phi(y, -x-y)y\Phi(y, -x-y)^{-1}e^{(x+y)/2}$$

Our main result (Theorem 2.1) is the identity

$$(2) \quad \Phi(t_{12}, t_{23}) \circ \mu_\Phi^{1,2,3} \circ \mu_\Phi^{1,2} = \mu_\Phi^{1,23} \circ \mu_\Phi^{2,3}.$$

This identity implies that the Jacobian of μ_Φ is a cocycle, and therefore a coboundary according to cohomology computations in [AT]; it can then be expressed using the Γ -function Γ_Φ of Φ (see [DT, E]). Identity (2) also implies that μ_Φ is special, i.e., satisfies

$$(3) \quad \mu_\Phi(\log(e^x e^y)) = x + y$$

Is this only true at the universal level, or also at every Lie-algebraic specialization?

(see Subsection 5.2 and also Proposition 7.4 in [AT]); we also give a direct proof of (3) based on the hexagon and duality identities satisfied by Φ . The conjunction of (3) and of the fact that the Jacobian of μ_Φ is a coboundary actually means that μ_Φ is a solution of the KV equations introduced in [AT].

The affine line of solutions of the KV equations attached in [AT] to Φ then takes the form $\{\text{Inn}(e^{s(x+y)}) \circ \mu_\Phi, s \in \mathbf{k}\}$, where $\text{Inn}(g) = (u \mapsto gug^{-1})$. It remains an open question whether all the solutions of the KV equation are of this form.

The strategy for proving (2) is as follows. For each associator Φ and each parenthesization O of a word in n identical letters (the letter is \bullet), Drinfeld and Bar-Natan define an isomorphism $\tilde{\mu}_\Phi^O : \text{PB}_n(\mathbf{k}) \rightarrow \exp(\hat{\mathfrak{t}}_n)$ from the pronipotent completion of the pure braid group with n strands to the group associated with the holonomy Lie algebra. Note that PB_n contains the free group F_{n-1} as a normal subgroup, while \mathfrak{t}_n contains the free Lie algebra \mathfrak{f}_{n-1} as an ideal; we show that the above isomorphisms restrict to isomorphisms $\mu_\Phi^O : F_{n-1}(\mathbf{k}) \rightarrow \exp(\hat{\mathfrak{f}}_{n-1})$ (in the case of the left parenthesization, this was proved in [HM]). We note that μ_Φ may be interpreted as the isomorphism $F_2(\mathbf{k}) \rightarrow \exp(\hat{\mathfrak{f}}_2)$ corresponding to $\bullet(\bullet\bullet)$, so $\mu_\Phi = \mu_{\bullet(\bullet\bullet)}$ (we write μ_O instead of μ_Φ^O when no confusion is possible). We then show the identity

$$(4) \quad \mu_{O^{(i)}} = \mu_O^{1,2,\dots,ii+1,\dots,n} \circ \mu_{\bullet(\bullet\bullet)}^{i,i+1},$$

where O is a parenthesized word of length n and $O^{(i)}$ is the parenthesized word obtained from it by replacing the $(i+1)$ th letter \bullet by $\bullet(\bullet)$. Applying this identity to $O = \bullet(\bullet\bullet)$ with $i = 1, 2$ and using the identity $\mu_\Phi^{O'} = \text{Ad}(\Phi_{O,O'}) \circ \mu_\Phi^O$ relating the various μ_Φ^O , we obtain (2).

We then study the torsor aspects of the map $\Phi \mapsto \mu_\Phi$. While $M_1(\mathbf{k})$ is a torsor under the commuting actions of the groups $\text{GT}_1(\mathbf{k})$ and $\text{GRT}_1(\mathbf{k})$, $\text{SolKV}(\mathbf{k})$ is a torsor under the actions of groups $\text{KV}(\mathbf{k})$ and $\text{KRV}(\mathbf{k})$. We prove that $\Phi \mapsto \mu_\Phi$ is a morphism of torsors, i.e., there exist group morphisms $\text{GT}_1(\mathbf{k}) \rightarrow \text{KV}(\mathbf{k})$, $f \mapsto \alpha_f$ and $\text{GRT}_1(\mathbf{k}) \rightarrow \text{KRV}(\mathbf{k})$, $g \mapsto a_g$, compatible with the actions (the Lie algebra version of the latter morphism was already constructed in [AT]). We give a direct proof of these facts, based on the nonemptiness of $M_1(\mathbf{k})$ (a result in [Dr]); we also sketch an independent proof of $\alpha_f \in \text{KV}(\mathbf{k})$; its main ingredient is the identity

$$(5) \quad \text{Ad } f(x_{12}, x_{23}) \circ \alpha_f^{\overline{12,3}} \circ \alpha_f^{1,2} = \alpha_f^{\overline{1,23}} \circ \alpha_f^{2,3}.$$

A similar independent proof of $a_g \in \text{KRV}(\mathbf{k})$ may be given based on

$$\text{Ad } g(t_{12}, t_{23}) \circ a_g^{\overline{12,3}} \circ a_g^{1,2} = a_g^{\overline{1,23}} \circ a_g^{2,3}.$$

It can be proved using the techniques of [AT] that the sets of solutions of both equations are affine lines, and our result gives explicit formulas for these solutions. We also observe that (5) can be generalized to the profinite and pro- l setups (i.e., we have morphisms $\widehat{\text{GT}} \rightarrow \text{Aut}(\widehat{F}_2)$ and $\text{GT}_l \rightarrow \text{Aut}((F_2)_l)$, $f \mapsto \alpha_f$, and (5) takes place in $\text{Aut}(\widehat{F}_3)$ or $\text{Aut}((F_3)_l)$).

Formula (4) and its analogue (5) then enable us to compute the Jacobians of $\mu_\Phi^O : F_{n-1}(\mathbf{k}) \rightarrow \exp(\mathfrak{f}_{n-1})$ and $\alpha_f^O \in \text{Aut}(F_{n-1}(\mathbf{k}))$, where O is an arbitrary parenthesized word, $\Phi \in M_1(\mathbf{k})$, $f \in \text{GT}_1(\mathbf{k})$, in terms of Γ_Φ and of the ‘ Γ -function’ of f .

Finally, we show that specializing our construction to the Knizhnik–Zamolodchikov (KZ) associator yields an explicit solution of the original KV conjecture, where the Lie series are required to converge for any finite dimensional Lie algebra and the Duflo series is required to coincide with the generating series of Bernoulli numbers.

Acknowledgements. We are grateful to V.G. Drinfeld and to D. Bar-Natan who posed the question of how to construct explicit solutions of the KV problem in terms of associators. The formula for μ_Φ as well as the proof of equation (3) were suggested to us by D. Calaque. We would like to thank G. Massuyeau for discussions and for pointing out reference [HM].

The research of A.A. was supported in part by the grants 200020-120042 and 200020-121675 of the Swiss National Science Foundation, and the research of C.T. was supported by CNRS.

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I. PRELIMINARY RESULTS

In this section, we recall the notions of tangential derivations and automorphisms of free Lie algebras, their divergence and Jacobian cocycles, the actions of pure braid groups (resp., infinitesimal braid Lie algebras) on free groups Lie algebras by tangential automorphisms (resp., derivations), and simplicial morphisms between these objects.

1.1. Tangential automorphisms, the Jacobian cocycle, and complexes. Let f_n be the free Lie algebra with generators x_1, \dots, x_n , \hat{f}_n its degree completion (where the generators x_k have degree 1). For $u_1, \dots, u_n \in f_n$, we denote by $\llbracket u_1, \dots, u_n \rrbracket$ the derivation of f_n given by $x_k \mapsto [u_k, x_k]$. In this way, we define a linear map $(f_n)^n \rightarrow \text{Der}(f_n)$. Its image is a (positively) graded Lie subalgebra \mathfrak{tder}_n of $\text{Der}(f_n)$; its elements are called the tangential derivations of f_n . We similarly define $\mathfrak{tder}_n^\wedge \subset \text{Der}(\hat{f}_n)$ as the degree completion of \mathfrak{tder}_n ; it is a pronilpotent Lie algebra.

If $U_1, \dots, U_n \in \exp(\hat{f}_n)$, we similarly define $\llbracket U_1, \dots, U_n \rrbracket$ as the automorphism of \hat{f}_n given by $x_k \mapsto U_k x_k U_k^{-1}$. This defines a map $\exp(\hat{f}_n)^n \rightarrow \text{Aut}(\hat{f}_n)$, whose image is the subgroup of tangential automorphisms $\text{TAut}_n \subset \text{Aut}(\hat{f}_n)$. The exponential sets up an isomorphism $\exp : \mathfrak{tder}_n^\wedge \xrightarrow{\sim} \text{TAut}_n$.

Define $\mathfrak{T}_n := A_n/[A_n, A_n]$ as the quotient of the free associative algebra $A_n \simeq U(f_n)$ by its subspace of commutators; this is the vector space spanned by the set of cyclic words in x_1, \dots, x_n . \mathfrak{T}_n is equipped with an action of $\text{Der}(f_n)$, induced by the action of $\text{Der}(f_n)$ on A_n . We denote by $x \mapsto \langle x \rangle$ the canonical projection map $A_n \rightarrow \mathfrak{T}_n$. \mathfrak{T}_n is positively graded and we denote by $\hat{\mathfrak{T}}_n$ its degree completion; it is equipped with actions of $\text{Der}(\hat{f}_n)$ and $\text{Aut}(\hat{f}_n)$.

One shows that any $u \in \mathfrak{tder}_n$ can be written as $u = \llbracket u_1, \dots, u_n \rrbracket$, where (u_1, \dots, u_n) is uniquely determined by the condition $p_1(u_1) = \dots = p_n(u_n) = 0$, where $p_k : f_n \rightarrow \mathbf{k}$ is the linear map such that $u = \sum_k p_k(u) x_k$ modulo $\llbracket f_n, f_n \rrbracket$.

We define simplicial group morphisms $\text{TAut}_n \rightarrow \text{TAut}_m$ as follows. Let $\phi : [m] \supset D_\phi \rightarrow [n]$ be a partially defined map, and let $(a_1, \dots, a_n) \in (f_n)^n$ be such that each a_k has vanishing linear term in x_k . We set $\llbracket a_1, \dots, a_n \rrbracket^\phi := \llbracket b_1, \dots, b_m \rrbracket$, where $b_\ell(x_1, \dots, x_m) := a_{\phi(\ell)}(\sum_{k \in \phi^{-1}(1)} x_k, \dots, \sum_{k \in \phi^{-1}(n)} x_k)$. This formula defines a Lie algebra morphism $\mathfrak{tder}_n \rightarrow \mathfrak{tder}_m$, which induces a group morphism $\text{TAut}_n \rightarrow \text{TAut}_m$, also denoted $x \mapsto x^\phi$. We will also use the notation $x^\phi = x^{\phi^{-1}(1), \dots, \phi^{-1}(n)}$. For example, $\llbracket a_1, a_2 \rrbracket^{12,3} = \llbracket a_1(x_1 + x_2, x_3), a_1(x_1 + x_2, x_3), a_2(x_1 + x_2, x_3) \rrbracket$.

We also define noncommutative variants of these morphisms as follows. Let $\tilde{\phi}$ be a pair consisting of a partially defined map $\phi : [m] \supset D_\phi \rightarrow [n]$ as above and of total orders on each of the sets $\phi^{-1}(1), \dots, \phi^{-1}(n)$. We define $\llbracket a_1, \dots, a_n \rrbracket^{\tilde{\phi}} := \llbracket \tilde{b}_1, \dots, \tilde{b}_m \rrbracket$, where $\tilde{b}_\ell(x_1, \dots, x_m) := a_{\phi(\ell)}(\text{cbh}(x_k | k \in \phi^{-1}(1)), \dots, \text{cbh}(x_k | k \in \phi^{-1}(n)))$; here $\text{cbh}(a_1, \dots, a_p) = \log(e^{a_1} \dots e^{a_p})$ and $\text{cbh}(a_s | s \in S)$ is defined similarly, for S a finite ordered set. We use the notation $x^{\tilde{\phi}} = x^{\phi^{-1}(1), \dots, \phi^{-1}(n)}$ (where the elements of $\phi^{-1}(k)$ are written in increasing order).

We then define a ‘divergence’ map

$$j : \mathfrak{tder}_n \rightarrow \mathfrak{T}_n$$

as follows. Let $\partial_k : A_n \rightarrow A_n$ be the linear maps defined by the identity $x = \epsilon(x)1 + \sum_{k=1}^n x_k \partial_k(x)$ (where $\epsilon : A_n \rightarrow \mathbf{k}$ is the counit map). We then set

$$j(u) := \left\langle \sum_{k=1}^n x_k \partial_k(u_k) \right\rangle.$$

¹We set $[n] := \{1, \dots, n\}$.

One can show that j satisfies the cocycle identity

$$j([u, v]) = u \cdot j(v) - v \cdot j(u),$$

where the action of $\mathfrak{D}\mathfrak{er}_n$ on \mathfrak{T}_n is understood in the r.h.s.; j is graded, so it extends to a cocycle $\mathfrak{D}\mathfrak{er}_n^\hbar \rightarrow \hat{\mathfrak{T}}_n$. The Lie algebra cocycle j gives rise to the ‘Jacobian’ group cocycle

$$J : \text{TAut}_n \rightarrow \hat{\mathfrak{T}}_n.$$

J is uniquely defined by the conditions $J(\text{id}) = 0$ and $(d/dt)J(e^{tx}g)|_{t=0} = j(x) + x \cdot J(g)$; as a consequence, J satisfies the cocycle identity $J(h \circ g) = J(h) + h \cdot J(g)$.

The compatibility of j, J with simplicial maps can be described as follows. Any partially defined $[m] \supset D_\phi \xrightarrow{\phi} [n]$ gives rise to a Lie algebra morphism $\mathfrak{f}_n \rightarrow \mathfrak{f}_m, x' \mapsto x^\phi$, with $x_k^\phi := \sum_{\ell \in \phi^{-1}(k)} x_\ell$, and any $\tilde{\phi}$ gives rise to a morphism $\hat{\mathfrak{f}}_n \rightarrow \hat{\mathfrak{f}}_m, x \mapsto x^{\tilde{\phi}}$, with $x_k^{\tilde{\phi}} = \text{cbh}(x_\ell | \ell \in \tilde{\phi}^{-1}(k))$. These morphisms give rise to linear maps $\mathfrak{T}_n \rightarrow \mathfrak{T}_m$ and $\hat{\mathfrak{T}}_n \rightarrow \hat{\mathfrak{T}}_m$. Then one can show that $j(u^\phi) = j(u)^\phi, J(g^\phi) = J(g)^\phi, j(u^{\tilde{\phi}}) = j(u)^{\tilde{\phi}}, J(g^{\tilde{\phi}}) = J(g)^{\tilde{\phi}}$.

We define a complex $\mathfrak{T}_1 \xrightarrow{\delta} \mathfrak{T}_2 \xrightarrow{\delta} \mathfrak{T}_3 \dots$ by $f(x_1) \mapsto f(x_1 + x_2) - f(x_1) - f(x_2) = f^{12} - f^1 - f^2, f(x_1, x_2) \mapsto f(x_1 + x_2, x_3) - f(x_1, x_2 + x_3) - f(x_2, x_3) + f(x_1, x_2) = f^{12,3} - f^{1,23} - f^{2,3} + f^{1,2}$, etc. It is proved in [AT] that this complex is acyclic in degree 2 (the degree of \mathfrak{T}_i is i). The kernel of $\mathfrak{T}_1 \xrightarrow{\delta} \mathfrak{T}_2$ is 1-dimensional, spanned by the class of $x_1 \in A_1 \simeq \mathfrak{T}_1$.

We similarly define a complex $\hat{\mathfrak{T}}_1 \xrightarrow{\delta} \hat{\mathfrak{T}}_2 \xrightarrow{\delta} \hat{\mathfrak{T}}_3 \dots$ by $f(x_1) \mapsto f(\log(e^{x_1}e^{x_2})) - f(x_1) - f(x_2) = f^{12} - f^1 - f^2, f(x_1, x_2) \mapsto f(\log(e^{x_1}e^{x_2}), x_3) - f(x_1, \log(e^{x_2}e^{x_3})) - f(x_2, x_3) + f(x_1, x_2)$. It has a decreasing filtration by the degree, and its associated graded is the above complex, so the complex $\hat{\mathfrak{T}}_1 \xrightarrow{\delta} \dots$ is again acyclic in degree 2. Since $\log(e^{x_1}e^{x_2}) - x_1 - x_2$ is a sum of brackets, $\text{Ker}(\hat{\mathfrak{T}}_1 \xrightarrow{\delta} \hat{\mathfrak{T}}_2)$ is again 1-dimensional, spanned by the class of $x_1 \in A_1^\hbar \simeq \hat{\mathfrak{T}}_1$.

1.2. Braid groups and Lie algebras of infinitesimal braids. Let B_n be the braid group of order n . B_n may be viewed as $\pi_1(X_n/S_n, S_n p)$, where $X_n = \{(z_1, \dots, z_n) \in \mathbb{C}^n | z_i \neq z_j \text{ if } i \neq j\}$ and $S_n p$ is the S_n -orbit of the set $p = \{(z_1, \dots, z_n) | z_i \in \mathbb{R}, z_1 < \dots < z_n\}$. The fibration $X_n \rightarrow X_n/S_n$ gives rise to the morphism $B_n \rightarrow S_n$, and the pure braid group PB_n is defined as $\text{Ker}(B_n \rightarrow S_n)$, so we have an exact sequence $1 \rightarrow PB_n \rightarrow B_n \rightarrow S_n \rightarrow 1$; also $PB_n = \pi_1(X_n, p)$.

We recall the Artin presentation of B_n : generators are $\sigma_1, \dots, \sigma_{n-1}$, and relations are given by

$$\sigma_i \sigma_{i+1} \sigma_i = \sigma_{i+1} \sigma_i \sigma_{i+1} \quad (i = 1, \dots, n-2), \quad \sigma_i \sigma_j = \sigma_j \sigma_i \text{ for } |i - j| > 1.$$

We also recall the Coxeter presentation of S_n : generators are s_1, \dots, s_{n-1} (s_i is the permutation $(i, i + 1)$) and relations are the same as those between the σ_i , with the additional relations $s_i^2 = 1$ ($i = 1, \dots, n-1$). The morphism $B_n \rightarrow S_n$ is then given by $\sigma_i \mapsto s_i$.

The group PB_n admits the following presentation. For $i < j$ ($i, j \in [n]$), set

$$x_{ij} := (\sigma_{j-2} \dots \sigma_i)^{-1} \sigma_{j-1}^2 (\sigma_{j-2} \dots \sigma_i).$$

The generators x_{ij} belong to PB_n , and²

$$(x_{ij} x_{ik} x_{jk}, x_{ij}) = (x_{ij} x_{ik} x_{jk}, x_{ik}) = (x_{ij} x_{ik} x_{jk}, x_{jk}) = 1 \text{ for } i < j < k,$$

and

$$(x_{ij}, x_{kl}) = (x_{il}, x_{jk}) = (x_{ik}, x_{jl} x_{jk}^{-1}) = 1 \text{ for } i < j < k < l.$$

One proves that this constitutes a presentation of PB_n , see Figure 1.

For any sequence (k_1, \dots, k_n) of integers ≥ 0 , there exists a unique morphism $PB_n \rightarrow PB_{k_1 + \dots + k_n}$ consisting in replacing the first strand by k_1 consecutive strands, ..., the n th strand by k_n consecutive strands. If we set $m := k_1 + \dots + k_n$ and $\phi : [m] \rightarrow [n]$ is

²We set $(g, h) := ghg^{-1}h^{-1}$.

the map such that $\phi(k_1 + \dots + k_{i-1} + [k_i]) = i$, we denote this morphism by $x \mapsto x^\phi = x^{\widehat{1\dots k_1\dots k_1+\dots+k_{n-1}+1\dots m}}$. This morphism is explicitly given by

$$x_{ij} \mapsto \prod_{i' \in \phi^{-1}(i)}^{\leftarrow} \left(\prod_{j' \in \phi^{-1}(j)}^{\rightarrow} x_{i'j'} \right),$$

where $\prod^{\leftarrow}, \prod^{\rightarrow}$ mean the product in increasing and decreasing order of the indices.

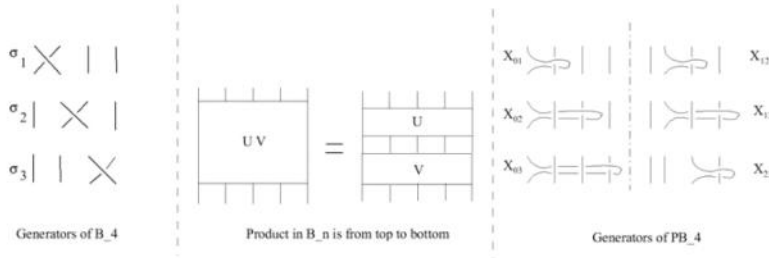


FIGURE 1.

The Lie algebra \mathfrak{t}_n of infinitesimal braids is presented by generators $t_{ij}, i \neq j \in [n]$ and relations $t_{ji} = t_{ij}, [t_{ij}, t_{ik} + t_{jk}] = 0$ for i, j, k distinct and $[t_{ij}, t_{kl}] = 0$ for i, j, k, l distinct. For each partially defined map $[m] \supset D_\phi \xrightarrow{\phi} [n]$, there is a unique Lie algebra morphism $\mathfrak{t}_n \rightarrow \mathfrak{t}_m, x \mapsto x^\phi$ given by $t_{ij}^\phi := \sum_{i' \in \phi^{-1}(i), j' \in \phi^{-1}(j)} t_{i'j'}$ (in particular, we have an action of S_n on \mathfrak{t}_n). We often write $x^{\phi^{-1}(1)\dots\phi^{-1}(n)}$ instead of x^ϕ . We attribute degree 1 to each of the generators t_{ij} , so the Lie algebra \mathfrak{t}_n is positively graded; we denote by $\hat{\mathfrak{t}}_n$ its degree completion.

1.3. The morphism $\mathfrak{t}_{n+1} \rightarrow \mathfrak{tder}_n$. Let us reindex $t_{ij}, i \neq j \in \{0, \dots, n\}$ the generators of \mathfrak{t}_{n+1} . One checks that there is a unique morphism $\text{ad} : \mathfrak{t}_{n+1} \rightarrow \mathfrak{tder}_n$, defined by $t_{0i} \mapsto (x_j \mapsto [x_i, x_j])$ and $t_{ij} \mapsto (x_i \mapsto [x_i, x_j], x_j \mapsto [x_j, x_i], x_k \mapsto 0$ for $k \neq i, j$) if $i, j \neq 0$. It exponentiates to $\text{Ad} : \exp(\hat{\mathfrak{t}}_{n+1}) \rightarrow \text{TAut}_n$. One checks that $j(\text{ad } t_{ij}) = 0$, so the cocycle property implies $j(\text{ad } x) = J(\text{Ad } X) = 0$ for any $x \in \mathfrak{t}_{n+1}$ and $X \in \exp(\hat{\mathfrak{t}}_{n+1})$.

The morphism $\text{ad} : \mathfrak{t}_{n+1} \rightarrow \mathfrak{tder}_n$ may be interpreted as follows. The Lie subalgebra of \mathfrak{t}_{n+1} generated by the elements $t_{0i}, i \in [n]$ identifies with \mathfrak{f}_n under $x_i \mapsto t_{0i}$; it is a Lie ideal of \mathfrak{t}_{n+1} . Then $\text{ad} : \mathfrak{t}_{n+1} \rightarrow \text{Der}(\mathfrak{f}_n)$ can be viewed as the adjoint action of \mathfrak{t}_{n+1} on its Lie ideal $\mathfrak{f}_n \subset \mathfrak{t}_{n+1}$.

Note that the morphism $\mathfrak{t}_n \rightarrow \mathfrak{t}_{n+1}, t_{ij} \mapsto t_{ij}$ is injective, so \mathfrak{t}_n may be viewed as a Lie subalgebra of \mathfrak{t}_{n+1} ; then \mathfrak{t}_{n+1} identifies with the semidirect product $\mathfrak{f}_n \rtimes_{\text{ad}} \mathfrak{t}_n$.

1.4. The morphism $\text{PB}_{n+1} \rightarrow \text{TAut}_n$. Reindex the generators of PB_{n+1} as $x_{ij}, i < j \in \{0, \dots, n\}$. Let F_n be the free group with generators $X_i (i \in [n])$. Then: (a) the morphism $F_n \rightarrow \text{PB}_{n+1}, X_i \mapsto x_{0i}$, is injective; (b) F_n is a normal subgroup in PB_{n+1} . This implies that we have an action $\text{Ad} : \text{PB}_{n+1} \rightarrow \text{Aut}(F_n)$ of PB_n by automorphisms of F_n .

This action can be made explicit as follows: if $i > 0$, then

$$\text{Ad}(x_{0i})(X_j) = X_i X_j X_i^{-1},$$

and if $0 < i < j$, then

$$\begin{aligned} \text{Ad}(x_{ij})(X_i) &= X_j^{-1}X_iX_j, & \text{Ad}(x_{ij})(X_j) &= (X_iX_j)^{-1}X_j(X_iX_j), \\ \text{Ad}(x_{ij})(X_k) &= X_k \text{ for } k < i \text{ or } k > j, \\ \text{Ad}(x_{ij})(X_k) &= (X_j^{-1}X_i^{-1}X_jX_i)X_k(X_j^{-1}X_i^{-1}X_jX_i)^{-1} \text{ for } i < k < j. \end{aligned}$$

This extends to an action of PB_{n+1} by automorphisms of $F_n(\mathbf{k})$. Using the isomorphism $F_n(\mathbf{k}) \simeq \exp(\hat{f}_n)$ given by $X_i \mapsto e^{x_i}$, we therefore obtain a morphism $\text{PB}_n \rightarrow \text{Aut}(\hat{f}_n)$. Its image is contained in TAut_n (since $\text{Ad } x_{ij}$ belongs to this subgroup and the elements x_{ij} generate PB_n), and since TAut_n is pronipotent, the universal property of Malcev completions implies that Ad extends to a morphism $\text{Ad} : \text{PB}_n(\mathbf{k}) \rightarrow \text{TAut}_n$.

Lemma 1.1. *For any $g \in \text{PB}_{n+1}(\mathbf{k})$, $J(\text{Ad } g) = 0$.*

Proof. It suffices to show that $J(\text{Ad } x_{ij}) = 0$. For any $u \in F_n(\mathbf{k})$, $J(\text{Inn } u) = 0$ (where $\text{Inn } u$ is $v \mapsto uvu^{-1}$) and $\text{Ad}(x_{0i}) = \text{Inn}(X_i)$, so it suffices to prove that $J(\text{Inn } X_j \circ \text{Ad } x_{ij}) = 0$ for $0 < i < j$. Let $\theta_{ij} := \text{Inn } X_j \circ \text{Ad } x_{ij}$, then $\theta_{ij} : X_i \mapsto X_i, X_j \mapsto X_i^{-1}X_jX_i, X_k \mapsto X_jX_kX_j^{-1}$ for $k < i$ or $k > j, X_k \mapsto (X_i^{-1}X_jX_i)X_k(X_i^{-1}X_jX_i)^{-1}$ for $i < k < j$.

Let $\mathfrak{u} \subset \mathfrak{tder}_n^\wedge$ be the subspace of all elements $\llbracket a_1, \dots, a_n \rrbracket$, where $a_j \in \mathfrak{k}x_i, a_i = 0$, and for $k \neq i, j, a_k \in \hat{f}_n$ has the form $a_k(x_i, x_j)$ ($a_k \in \hat{f}_2$). This is a Lie subalgebra in \mathfrak{tder}_n^\wedge , so exp maps it bijectively to a subgroup of TAut_n . One checks that $\exp(\mathfrak{u}) \subset U$, where $U \subset \text{TAut}_n$ is the subspace of all $\llbracket U_1, \dots, U_n \rrbracket$, where $U_j \in \{e^{\lambda x_i}, \lambda \in \mathbf{k}\}, U_i = 1$, and for $k \neq i, j, U_k$ has the form $U_k(x_i, x_j)$ ($U_k \in \exp(\hat{f}_2)$), and that U is an algebraic subgroup of TAut_n . Therefore $\mathfrak{u} \subset \text{Lie}(U)$. On the other hand, one checks that \mathfrak{u} coincides with the tangent subspace of U at the origin, so $\mathfrak{u} = \text{Lie}(U)$. It follows that log takes U to \mathfrak{u} .

All this implies that $\log \theta_{ij}$ has the form $\llbracket a_1, \dots, a_n \rrbracket$, where $a_i = 0, a_j = -x_i$ and for $k \neq i, j, a_k \in \hat{f}_n$ has the form $a_k(x_i, x_j)$. Then $j(\log \theta_{ij}) = 0$, hence $J(\theta_{ij}) = 0$, as wanted. \square

Note that the quotient group PB_{n+1}/F_n identifies with PB_n under $x_{ij} \mapsto x_{ij}$ for $0 < i < j, x_{0i} \mapsto 1$. We then have an exact sequence $1 \rightarrow F_n \rightarrow \text{PB}_{n+1} \rightarrow \text{PB}_n \rightarrow 1$. Moreover, this exact sequence admits the splitting $\text{PB}_n \rightarrow \text{PB}_{n+1}, x_{ij} \mapsto x_{ij}$. It follows that PB_{n+1} identifies with the semidirect product $F_n \rtimes_{\text{Ad}} \text{PB}_n$.

Remark 1.2. We will rename x, y (resp., x, y, z, X, Y, X, Y, Z) the generators x_1, x_2 (resp., $x_1, x_2, x_3, X, Y, X, Y, Z$) of \hat{f}_2 (resp., \hat{f}_3, F_2, F_3).

2. THE MAIN RESULTS

2.1. The map $M_1(\mathbf{k}) \rightarrow \text{SolKV}(\mathbf{k})$. Let \hat{f}_2 be the topologically free Lie algebra generated by x, y . Let F_2 be the free group with generators X, Y and let $F_2(\mathbf{k})$ be its pronipotent completion; we have an identification $F_2(\mathbf{k}) \simeq \exp(\hat{f}_2)$, induced by the morphism $F_2 \rightarrow \exp(\hat{f}_2)$ given by $X \mapsto e^x, Y \mapsto e^y$.

The set of solutions of the Kashiwara-Vergne equations is (see [KV, AT])^{3 4 5}

$$\begin{aligned} \text{SolKV}(\mathbf{k}) := \{ \mu \in \text{Iso}(F_2(\mathbf{k}), \exp(\hat{f}_2)) \mid \mu(X) \sim e^x, \mu(Y) \sim e^y, \mu(XY) = e^{x+y}, \\ \text{and } \exists r \in u^2\mathbf{k}[[u]] \mid J(\mu) = \langle r(x+y) - r(x) - r(y) \rangle \}. \end{aligned}$$

Here μ gives rise to an element of TAut_2 (using $F_2(\mathbf{k}) \simeq \exp(\hat{f}_2)$) and $J(\mu)$ is its Jacobian. As the kernel of $\mathfrak{T}_1 \rightarrow \mathfrak{T}_2$ is equal to $\mathfrak{k}u$, r is uniquely determined by $\mu \in \text{SolKV}(\mathbf{k})$, so we

³For g, h in a pronipotent group G or its Lie algebra, we use the notation $g \sim h$ for ' g is conjugated to h ', i.e., $g = khk^{-1}$ for some $k \in G$.

⁴If Γ is a finitely generated group, we denote by $\Gamma(\mathbf{k})$ its pronipotent (of Malcev) completion. There is a group morphism $\Gamma \rightarrow \Gamma(\mathbf{k})$ with the universal property that any group morphism $\Gamma \rightarrow U$, with U pronipotent, extends uniquely to a morphism $\Gamma(\mathbf{k}) \rightarrow U$ of algebraic groups.

⁵The definition given here is equivalent to that of [AT] as $\mathfrak{T}_1 \rightarrow \mathfrak{T}_2 \rightarrow \mathfrak{T}_3$ is acyclic.

define a map $\text{Duf} : \text{SolKV}(\mathbf{k}) \rightarrow u^2\mathbf{k}[[u]]$, $\mu \mapsto r = \text{Duf}(\mu)$; we will call r the Duflo formal series of μ .

The set of associators with coupling constant 1 is

$$M_1(\mathbf{k}) := \{\Phi(t_{12}, t_{23}) \in \exp(\hat{\mathfrak{t}}_3) | \Phi^{3,2,1} = \Phi^{-1}, e^{t_{23}/2} \Phi^{1,2,3} e^{t_{12}/2} \Phi^{3,1,2} e^{t_{31}/2} \Phi^{2,3,1} = e^{(t_{12}+t_{23}+t_{31})/2}, \Phi^{2,3,4} \Phi^{1,23,4} \Phi^{1,2,3} = \Phi^{1,2,34} \Phi^{12,3,4}\}.$$

Theorem 2.1. *There is a unique map $M_1(\mathbf{k}) \rightarrow \text{SolKV}(\mathbf{k})$, $\Phi \mapsto \mu_\Phi$, such that⁶*

$$\mu_\Phi(X) = \Phi(x, -x-y)e^x \Phi(x, -x-y)^{-1}, \mu_\Phi(Y) = e^{-(x+y)/2} \Phi(y, -x-y) \cdot e^y \cdot (\text{same})^{-1}.$$

The Jacobian of μ_Φ can be computed as follows. In [DT, E] (see also [Ih]), it was proved⁷ that for any $\Phi(a, b) \in M_1(\mathbf{k})$, there exists a formal series $\Gamma_\Phi(u) = e^{\sum_{n \geq 2} (-1)^n \zeta_\Phi(n) u^n/n}$, such that

$$(6) \quad (1 + b\partial_b \Phi(a, b))^{ab} = \frac{\Gamma_\Phi(\bar{a} + \bar{b})}{\Gamma_\Phi(\bar{a})\Gamma_\Phi(\bar{b})},$$

where $\partial_b \Phi(a, b)$ is defined as above and $x \mapsto x^{ab}$ is the abelianization morphism $\mathbf{k}\langle\langle a, b \rangle\rangle \rightarrow \mathbf{k}[[\bar{a}, \bar{b}]]$

The values of the $\zeta_\Phi(n)$ for n even are independent of Φ , given by $-\frac{1}{2}(\frac{u}{e^u-1} - 1 + \frac{u}{2}) = \sum_{n \geq 1} \zeta_\Phi(2n) u^{2n}$, so they are related to Bernoulli numbers by $\zeta_\Phi(2n) = -\frac{1}{2} \frac{B_{2n}}{(2n)!}$ for $n \geq 1$ (we have $\zeta_\Phi(2) = -1/24$, $\zeta_\Phi(4) = 1/1440$, etc.)

Proposition 2.2. $J(\mu_\Phi) = \langle \log \Gamma_\Phi(x) + \log \Gamma_\Phi(y) - \log \Gamma_\Phi(x+y) \rangle$, so $\text{Duf}(\mu_\Phi) = -\log \Gamma_\Phi$.

2.2. Torsor aspects. We set

$$\text{KV}(\mathbf{k}) := \{\alpha \in \text{Aut}(\mathbb{F}_2(\mathbf{k})) | \alpha(X) \sim X, \alpha(Y) \sim Y, \alpha(XY) = XY, \text{ and } \exists \sigma \in u^2\mathbf{k}[[u]] | J(\alpha) = \langle \sigma(\log(e^x e^y)) - \sigma(x) - \sigma(y) \rangle\}$$

and

$$\text{KRV}(\mathbf{k}) := \{a \in \text{Aut}(\hat{\mathfrak{f}}_2) | a(x) \sim x, a(y) \sim y, a(x+y) = x+y, \text{ and } \exists s \in u^2\mathbf{k}[[u]] | J(a) = \langle s(x+y) - s(x) - s(y) \rangle\}.$$

Here α, a give rise to elements of TAut_2 (using $\mathbb{F}_2(\mathbf{k}) \simeq \exp(\hat{\mathfrak{f}}_2)$) and $J(\alpha), J(a)$ are their Jacobians. As before, we will denote $\text{Duf} : \text{KV}(\mathbf{k}) \rightarrow u^2\mathbf{k}[[u]]$, $\text{KRV}(\mathbf{k}) \rightarrow u^2\mathbf{k}[[u]]$ the maps $\alpha \mapsto \sigma, a \mapsto s$.

Proposition 2.3. *$\text{KV}(\mathbf{k})$ and $\text{KRV}(\mathbf{k})$ are groups. $\text{SolKV}(\mathbf{k})$ is a torsor under the commuting left action of $\text{KV}(\mathbf{k})$ and right action of $\text{KRV}(\mathbf{k})$ given by $(\alpha, \mu) \mapsto \mu \circ \alpha^{-1}$ and $(\mu, a) \mapsto a^{-1} \circ \mu$.*

⁶If G is a pronilpotent group, we use the notation $g \cdot h \cdot (\text{same})^{-1}$ for ghg^{-1} for $g \in G$ and $h \in G$ or $\text{Lic}(G)$.

⁷The key ingredient in the proof of this result is the statement that the image of grt_1 in $\mathfrak{f}'_2/\mathfrak{f}''_2$ is spanned by the classes of the Drinfeld generators. This statement also follows from Theorem 4.1 in [AT]; indeed, one sees easily that the diagram

$$\begin{array}{ccc} \mathfrak{f}_2 & \xrightarrow{\psi \mapsto (ad_a \psi)} & \mathfrak{F}_2 & \xrightarrow{\phi \mapsto \phi^{ab}} & \mathbf{k}[\bar{a}, \bar{b}] \\ \uparrow & & & & \uparrow \\ \mathfrak{f}'_2 & & \rightarrow & & \mathfrak{f}'_2/\mathfrak{f}''_2 = \overline{ab}\mathbf{k}[\bar{a}, \bar{b}] \\ \uparrow & & & & \uparrow \\ \text{grt}_1 & & \rightarrow & & \text{grt}_1/\text{grt}'_1 \end{array}$$

commutes (the upper part follows from the fact that \mathfrak{f}'_2 is freely generated by the $(ad a)^k (ad b)^l ([a, b])$ and the bottom part from $\text{grt}'_1 \subset \mathfrak{f}'_2$); Theorem 4.1 in [AT] implies that the image of $\text{grt}_1 \rightarrow \mathfrak{F}_2$ is spanned by the images of the Drinfeld generators; it follows that the same is true of the image of $\text{grt}_1 \rightarrow \mathfrak{f}'_2/\mathfrak{f}''_2$.

In particular, any element of $\text{SolKV}(\mathbf{k})$ gives rise to an isomorphism $\mathfrak{t}\mathfrak{v} \rightarrow \mathfrak{t}\mathfrak{v}$ between the Lie algebras of these groups, whose associated graded is the canonical identification $\text{gr}(\mathfrak{t}\mathfrak{v}) \simeq \mathfrak{t}\mathfrak{v}$.

The pronilpotent radical of the Grothendieck-Teichmüller group is

$$\text{GT}_1(\mathbf{k}) = \{f(X, Y) \in \mathbb{F}_2(\mathbf{k}) \mid f(Y, X) = f(X, Y)^{-1}, f(X, Y)f(Y^{-1}X^{-1}, X)f(Y, Y^{-1}X^{-1}) = 1, \\ f(x_{23}, x_{34})f(x_{12}x_{13}, x_{24}x_{34})f(x_{12}, x_{23}) = f(x_{12}, x_{23}x_{24})f(x_{13}x_{23}, x_{34})\}$$

(the last equation is in $\text{PB}_4(\mathbf{k})$) with product $(f_1 * f_2)(X, Y) = f_1(f_2(X, Y)Xf_2(X, Y)^{-1}, Y)f_2(X, Y)$. Its graded version is

$$\text{GRT}_1(\mathbf{k}) = \{g(t_{12}, t_{23}) \in \exp(\mathfrak{k}_3) \mid g^{3,2,1} = g^{-1}, g(A, C)Ag(A, C)^{-1} + g(B, C)Bg(B, C)^{-1} + C = 0 \\ \text{for } A + B + C = 0, g^{1,2,3}g^{3,1,2}g^{2,3,1} = 1, g^{2,3,4}g^{1,2,3,4}g^{1,2,3} = g^{1,2,3,4}g^{1,2,3,4}\}$$

with product $(g_1 * g_2)(a, b) = g_1(g_2(a, b)ag_2(a, b)^{-1}, b)g_2(a, b)$ (we set $a := t_{12}, b := t_{23}$).

Proposition 2.4. (see [Dr]) $M_1(\mathbf{k})$ is a torsor under the commuting left action of $\text{GT}_1(\mathbf{k})$ and right action of $\text{GRT}_1(\mathbf{k})$ by $(f, \Phi) \mapsto (f * \Phi)(a, b) := f(\Phi(a, b)e^a\Phi(a, b)^{-1}, e^b)\Phi(a, b)$ and $(\Phi, g) \mapsto (\Phi * g)(a, b) := \Phi(g(a, b)ag(a, b)^{-1}, b)g(a, b)$.

The following Theorem 2.5 and Proposition 2.6 express torsor properties of the map $\Phi \mapsto \mu_\Phi$.

Theorem 2.5. There are unique group morphisms $\text{GT}_1(\mathbf{k}) \rightarrow \text{KV}(\mathbf{k}), f(X, Y) \mapsto \alpha_f^{-1}$, where

$$\alpha_f(X) = f(X, Y^{-1}X^{-1})Xf(X, Y^{-1}X^{-1})^{-1}, \alpha_f(Y) = f(Y, Y^{-1}X^{-1})Yf(Y, Y^{-1}X^{-1})^{-1},$$

and $\text{GRT}_1(\mathbf{k}) \rightarrow \text{KRV}_1(\mathbf{k}), g(a, b) \mapsto a_g^{-1}$, where

$$a_g(x) = g(x, -x - y)yg(x, -x - y)^{-1}, a_g(y) = g(y, -x - y)yg(y, -x - y)^{-1}.$$

These group morphisms are compatible with the map $M_1(\mathbf{k}) \rightarrow \text{SolKV}(\mathbf{k})$, which is therefore a morphism of torsors.

Proposition 2.6. We have a commuting diagram of torsors

$$\begin{array}{ccc} M_1(\mathbf{k}) & \xrightarrow{\Phi \mapsto \mu_\Phi} & \text{SolKV}(\mathbf{k}) \\ \Phi \mapsto \log \Gamma_\Phi \downarrow & & \downarrow \text{Duf} \\ \{r \in u^2\mathbf{k}[[u]] \mid r_{\text{ev}}(u) = -\frac{u^2}{24} + \frac{u^4}{1440} \dots\} & \xrightarrow{(-1) \times} & u^2\mathbf{k}[[u]] \end{array}$$

where $r_{\text{ev}}(u)$ is the even part of $r(u)$, and the spaces in the lower line are viewed as affine spaces.

2.3. Analytic aspects. Let us recall the original form of the KV conjecture. Let $\mathbf{k} = \mathbb{R}$ or \mathbb{C} .

Conjecture 2.7. ([KV]) For any finite dimensional \mathbf{k} -Lie algebra \mathfrak{g} , there exists a pair of Lie series $A(x, y), B(x, y) \in \hat{\mathfrak{f}}_2$, such that:

(KV1) $x + y - \log e^ye^x = (1 - e^{-\text{ad } x})(A(x, y)) + (e^{\text{ad } y} - 1)(B(x, y));$

(KV2) A, B give convergent power series at the neighborhood of $(0, 0) \in \mathfrak{g}^2$;

(KV3) $\text{tr}_{\mathfrak{g}}((\text{ad } x)\partial_x A + (\text{ad } y)\partial_y B) = \frac{1}{2} \text{tr}_{\mathfrak{g}}(\frac{\text{ad } x}{e^{\text{ad } x} - 1} + \frac{\text{ad } y}{e^{\text{ad } y} - 1} - \frac{\text{ad } z}{e^{\text{ad } z} - 1} - 1)$ (identity of analytic functions on \mathfrak{g}^2 near the origin), where $z = \log e^xe^y$ and for $(x, y) \in \mathfrak{g}^2, (\partial_x A)(x, y) \in \text{End}(\mathfrak{g})$ is $a \mapsto \frac{d}{dt}|_{t=0} A(x + ta, y), (\partial_y B)(x, y)(a) = \frac{d}{dt}|_{t=0} B(x, y + ta)$.

According to [AT], there is a unique map $\kappa : \text{TAut}_2 \rightarrow \mathfrak{t}\text{Der}_2$, where $\kappa(g) := \ell - g\ell g^{-1}$, and $\ell \in \text{Der}(\hat{\mathfrak{f}}_2)$ is the ‘grading’ derivation $\ell(x_i) = x_i$. It is proved in [AT] that if $\mu \in \text{SolKV}(\mathbf{k})$, and (A, B) are such that $-\kappa(\mu^{-1}) = \llbracket A, B \rrbracket$, then (KV1) and (KV3) hold as identities between formal series for any \mathfrak{g} , where in (KV3) the formal series $\frac{1}{2} \frac{t}{e^t - 1}$ is replaced by $r_\mu(t)$.

Let $\Phi_{\text{KZ}}(a, b) \in \exp(\hat{\mathfrak{f}}_2)$ be the KZ associator, and $\tilde{\Phi}_{\text{KZ}}(a, b) := \Phi_{\text{KZ}}(\frac{a}{2\pi i}, \frac{b}{2\pi i})$; recall that $\tilde{\Phi}_{\text{KZ}}$ is the renormalized holonomy from 0 to 1 of $G'(t) = \frac{1}{2\pi i}(\frac{a}{t} + \frac{b}{t-1})G(t)$, and $\tilde{\Phi}_{\text{KZ}} \in M_1(\mathbb{C})$. Set $\mu_{\text{KZ}} := \mu_{\tilde{\Phi}_{\text{KZ}}}$ and $u_{\text{KZ}} = [A_{\text{KZ}}, B_{\text{KZ}}] := -\kappa(\mu_{\text{KZ}}^{-1})$.

Let $(A_{\mathbb{R}}, B_{\mathbb{R}})$ be defined as the real parts of $(A_{\text{KZ}}, B_{\text{KZ}})$ (w.r.t. the natural real structure of $\hat{\mathfrak{f}}_2$). Then:

Theorem 2.8. 1) $(A_{\mathbb{R}}, B_{\mathbb{R}})$ satisfies (KV1), (KV2) and (KV3) for any finite dimensional Lie algebra \mathfrak{g} and is therefore a universal solution of the KV conjecture.

2) For any $s \in \mathbb{R}$, $(A_s, B_s) := (A_{\mathbb{R}} + s(\log(e^x e^y) - x), B_{\mathbb{R}} + s(\log(e^x e^y) - y))$ is a universal solution of the KV conjecture.

3) When $s = -1/4$, we have $(A_s(x, y), B_s(x, y)) = (B_s(-y, -x), A_s(-y, -x))$.

Of course, the main new result here is the analyticity statement (KV2).

2.4. Organization of the proofs. We construct the isomorphisms $\tilde{\mu}_{\Phi}^O$ and μ_{Φ}^O in Section 3. In Section 4, we prove the identity relating μ_O and $\mu_{O(\cdot)}$. We then prove Theorem 2.1 and Proposition 2.2 in Section 5. In Section 6, we prove Proposition 2.3, Theorem 2.5 and Proposition 2.6. Section 7 is devoted to a direct proof of the properties of α_f . In Section 8, we compute the Jacobians of μ_{Φ}^O and α_f^O and in Section 9, we prove the analytic Theorem 2.8. Appendix A is devoted to results on centralizers in \mathfrak{t}_n and $\text{PB}_n(\mathbf{k})$.

3. ASSOCIATORS AND ISOMORPHISMS OF FREE GROUPS

3.1. The categories PaB, PaCD. In [B], Bar-Natan introduced the category **PaB** of parenthesized braids. Its set of objects is the set of pairs $O = (n, P)$, where n is an integer ≥ 0 and P is a parenthesization of the word $\bullet \dots \bullet$ (n letters); alternatively, P is a planar binary tree with n leaves (we will set $|O| = n$). The object with $n = 0$ is denoted $\mathbf{1}$. The morphisms are defined by $\text{PaB}(O, O') = \emptyset$ if $|O| \neq |O'|$, and $= \text{B}_n$ if $|O| = |O'| = n$; the composition is then defined using the product in B_n .

PaB is a braided monoidal category (see e.g. [CE]), where the tensor product of objects is $(n, P) \otimes (n', P') := (n + n', P * P')$ (where $P * P'$ is the concatenation of parenthesized words, e.g. for $P = \bullet \bullet$ and $P' = (\bullet \bullet) \bullet$, $P * P' = (\bullet \bullet)((\bullet \bullet) \bullet)$). The tensor product of morphisms $\text{PaB}(O_1, O'_1) \times \text{PaB}(O_2, O'_2) \rightarrow \text{PaB}(O_1 \otimes O_2, O'_1 \otimes O'_2)$ is induced by the juxtaposition of braids $\text{B}_{|O_1|} \times \text{B}_{|O_2|} \rightarrow \text{B}_{|O_1|+|O_2|}$ (the group morphism $(\sigma_i, \epsilon) \mapsto \sigma_i$, $(\epsilon, \sigma_j) \mapsto \sigma_{j+|O_1|}$). The braiding $\beta_{O, O'} \in \text{PaB}(O \otimes O', O' \otimes O)$ is the braid $\sigma_{n, n'} \in \text{B}_{n+n'}$ where the n first strands are globally exchanged with the n' last strands (see Figure 2); we have $\sigma_{n, n'} = (\sigma_n \dots \sigma_1)(\sigma_{n+1} \dots \sigma_2) \dots (\sigma_{n+n'-1} \dots \sigma_{n'})$ (where $n = |O|$, $n' = |O'|$). Finally, the associativity constraint $a_{O, O', O''} \in \text{PaB}((O \otimes O') \otimes O'', O \otimes (O' \otimes O''))$ corresponds to the trivial braid $\epsilon \in \text{B}_{|O|+|O'|+|O''|}$.

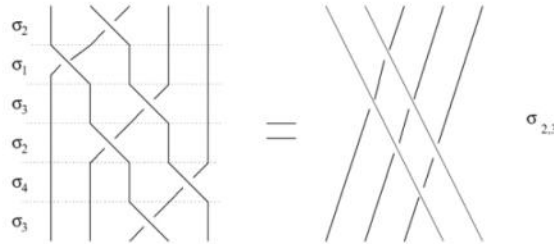


FIGURE 2.

Moreover, the pair (\mathbf{PaB}, \bullet) is universal for pairs (\mathcal{C}, M) of a braided monoidal category and an object, i.e., for each such pair, there exists a unique tensor functor $\mathbf{PaB} \rightarrow \mathcal{C}$ taking \bullet to M .

Bar-Natan introduced another category \mathbf{PaCD} , which we will describe as follows. Its set of objects is the same as that of \mathbf{PaB} , and $\mathbf{PaB}(O, O') = \emptyset$ if $|O| \neq |O'|$, $= \exp(\hat{t}_n) \rtimes S_n$ if $|O| = |O'| = n$. We define the tensor product as above at the level of objects, and by the juxtaposition map $(\exp \hat{t}_n \rtimes S_n) \times (\exp \hat{t}_n \rtimes S_n) \rightarrow \exp \hat{t}_{n+n'} \rtimes S_{n+n'}$ (the group morphism induced by $((t_{ij}, 1), 1) \mapsto t_{ij}, ((1, s_i), 1) \mapsto s_i, (1, (t_{ij}, 1)) \mapsto t_{n+i, n+j}, (1, (1, s_i)) \mapsto s_{n+i}$) at the level of morphisms).

Any $\Phi \in M_1(\mathbf{k})$ gives rise to a structure of braided monoidal category on \mathbf{PaCD} (and therefore to a tensor functor $\mathbf{PaB} \rightarrow \mathbf{PaCD}$, which is the identity at the level of objects) as follows: $\beta_{O, O'} = e^{\sum_{i=1}^n \sum_{j=n+1}^{n+n'} t_{ij}/2} s_{n, n'}$, where $n = |O|$, $n' = |O'|$, and $s_{n, n'} \in S_{n+n'}$ is given by $s_{n, n'}(i) = n' + i$ for $i \in [n]$, $s_{n, n'}(n+i) = i$ for $i \in [n']$, and $a_{O, O', O''} = \Phi(t_{12}, t_{23})^{1 \dots n, n+1 \dots n+n', n+n'+1 \dots n+n'+n''}$ for $n = |O|$, $n' = |O'|$, $n'' = |O''|$.

3.2. Morphisms $B_n \rightarrow \exp(\hat{t}_n) \rtimes S_n$, $PB_n \rightarrow \exp(\hat{t}_n)$. Fix $\Phi \in M_1(\mathbf{k})$. It gives rise to a functor $F_\Phi : \mathbf{PaB} \rightarrow \mathbf{PaCD}$, so for any $n \geq 1$ and any $O \in \text{Ob}(\mathbf{PaB})$, $|O| = n$, we get a group morphism

$$F_\Phi(O) = \tilde{\mu}_O : B_n \simeq \mathbf{PaB}(O) \rightarrow \mathbf{PaCD}(O) = \exp(\hat{t}_n) \rtimes S_n,$$

such that $\begin{array}{ccc} B_n & \xrightarrow{\tilde{\mu}_O} & \exp(\hat{t}_n) \rtimes S_n \\ \searrow & & \swarrow \\ S_n & & \end{array}$ commutes. It follows that $\tilde{\mu}_O$ restricts to a morphism

$$\tilde{\mu}_O : PB_n \rightarrow \exp(\hat{t}_n).$$

Let us show that the various $\tilde{\mu}_O$ are all conjugated to each other. Let $\text{can}_{O, O'} \in \mathbf{PaB}(O, O')$ correspond to $e \in B_n$. Then $\text{can}_{O', O''} \circ \text{can}_{O, O'} = \text{can}_{O, O''}$. Moreover, if we denote by $\sigma_O : B_n \rightarrow \mathbf{PaB}(O)$ the canonical identification, then $\sigma_{O'}(b) = \text{can}_{O, O'} \circ \sigma_O(b) \circ \text{can}_{O, O'}^{-1}$. Let us set $\Phi_{O, O'} := F_\Phi(\text{can}_{O, O'})$. Then:

- 1) $\Phi_{O, O'} \in \exp(\hat{t}_n)$, $\Phi_{O', O''} \Phi_{O, O'} = \Phi_{O, O''}$;
 - 2) $\tilde{\mu}_{O'}(b) = \Phi_{O, O'} \tilde{\mu}_O(b) \Phi_{O, O'}^{-1}$.
- If $O = \bullet(\dots(\bullet\bullet))$ is the 'right parenthesization', the explicit formula for $\tilde{\mu}_O$ is

$$\tilde{\mu}_O(\sigma_i) = \Phi^{i, i+1, i+2, \dots, n} e^{t_{i, i+1}/2} s_i(\Phi^{i, i+1, i+2, \dots, n})^{-1}, \quad i = 0, \dots, n-1.$$

The morphisms $\tilde{\mu}_O$ extend to isomorphisms between pronilpotent completions as follows. The pronilpotent completion of B_n relative to $B_n \rightarrow S_n$ will be denoted $B_n(\mathbf{k}, S_n)$; it may be constructed as follows: B_n acts by automorphisms of PB_n , hence of $PB_n(\mathbf{k})$; $B_n(\mathbf{k}, S_n)$ fits in an exact sequence $1 \rightarrow PB_n(\mathbf{k}) \rightarrow B_n(\mathbf{k}, S_n) \rightarrow S_n \rightarrow 1$ and identifies with the quotient of the semidirect product $PB_n(\mathbf{k}) \rtimes B_n$ by the image of the morphism $PB_n \rightarrow PB_n(\mathbf{k}) \rtimes B_n$, $g \mapsto (g^{-1}, g)$ (which is a normal subgroup). Then the morphisms $\tilde{\mu}_O$ give rise to isomorphisms

$$\begin{array}{ccc} PB_n(\mathbf{k}) & \xrightarrow{\simeq} & \exp(\hat{t}_n) \\ \downarrow & & \downarrow \\ B_n(\mathbf{k}, S_n) & \xrightarrow{\simeq} & \exp(\hat{t}_n) \rtimes S_n \end{array}$$

When Φ is the KZ associator (with coupling constant $2\pi i$), these isomorphisms are given by Sullivan's theory of minimal models applied to the configuration space of n points in the complex plane (which computes all the rational homotopy groups of a simply-connected Kaehler manifold, but only the Malcev completion of its fundamental group in the non-simply-connected case, whence the name '1-formality').

3.3. Restriction to free groups. Renumber x_{ij} , $i < j \in \{0, \dots, n\}$ and t_{ij} , $i \neq j \in \{0, \dots, n\}$ the generators for PB_{n+1} and \mathfrak{t}_{n+1} . Recall that PB_{n+1} contains the free group with n generators $F_n = \langle x_{01}, \dots, x_{0,n} \rangle$ as a normal subgroup. Similarly, \mathfrak{t}_{n+1} contains the free Lie algebra with n generators $\mathfrak{f}_n = \text{Lie}(t_{01}, \dots, t_{0,n})$. For coherence of notation with the previous sections, we will set $X_i := x_{0i}$, $x_i := t_{0i}$.

Proposition 3.1. *For any $O \in \text{Ob}(\text{PaB})$ with $|O| = n + 1$, the morphism $\tilde{\mu}_O$ restricts to a morphism $\mu_O : F_n \rightarrow \exp(\hat{\mathfrak{f}}_n)$, which extends to an isomorphism $\mu_O : F_n(\mathbf{k}) \rightarrow \exp(\hat{\mathfrak{f}}_n)$. The composition of μ_O with the isomorphism $\exp(\hat{\mathfrak{f}}_n) \rightarrow F_n(\mathbf{k})$, $\exp(x_i) \mapsto X_i$, is a tangential automorphism of $\exp(\hat{\mathfrak{f}}_n)$, i.e., an element of TAut_n .*

Proof. Let us first treat the case of $\mu_n := \mu_{\bullet(\dots(\bullet\bullet))}$. As $x_{0i} = (\sigma_{i-2}\dots\sigma_0)^{-1}\sigma_{i-1}^2(\sigma_{i-2}\dots\sigma_0)$, we have $\mu_n(x_{0i}) = \mu_n(\sigma_{i-2}\dots\sigma_0)^{-1}\Phi^{i-1,i,i+1,\dots,n} \cdot e^{t_{i-1,i}} \cdot (\Phi^{i-1,i,i+1,\dots,n})^{-1}\mu_n(\sigma_{i-2}\dots\sigma_0)$. There exists $y_i \in \hat{\mathfrak{t}}_{n+1}$ such that $\mu_n(\sigma_{i-2}\dots\sigma_0) = e^{y_i}\sigma_{i-2}\dots\sigma_0$, so for some $\tilde{y}_i \in \hat{\mathfrak{t}}_{n+1}$,

$$(\Phi^{i-1,i,i+1,\dots,n})^{-1}\mu_n(\sigma_{i-2}\dots\sigma_0) = \sigma_{i-2}\dots\sigma_0 e^{\tilde{y}_i}.$$

Then $\mu_n(x_{0i}) = e^{-\tilde{y}_i}(\sigma_{i-2}\dots\sigma_0)^{-1}e^{t_{i-1,i}}\sigma_{i-2}\dots\sigma_0 e^{\tilde{y}_i} = e^{-\tilde{y}_i}e^{t_{0i}}e^{\tilde{y}_i}$. As the action of $\hat{\mathfrak{t}}_{n+1}$ on $\hat{\mathfrak{f}}_n$ is by tangential automorphisms, we have $e^{-\tilde{y}_i}e^{t_{0i}}e^{\tilde{y}_i} = e^{z_i}e^{t_{0i}}e^{-z_i}$ for some $z_i \in \hat{\mathfrak{f}}_n$. So $\mu_n \circ (e^{t_{0i}} \mapsto x_{0i}) \in \text{TAut}_n$. The general case follows from the identity $\mu_{O'}(b) = \Phi_{O,O'}\mu_O(b)\Phi_{O,O'}^{-1}$ and the fact that for any $\Psi \in \exp(\hat{\mathfrak{t}}_{n+1})$, $x \mapsto \Psi x \Psi^{-1}$ induces a tangential automorphism of $\exp(\hat{\mathfrak{f}}_n)$. \square

Proposition 3.2. *If moreover $O = \bullet \otimes \bar{O}$, where $\bar{O} \in \text{Ob}(\text{PaB})$ has length n , then $\mu_O(X_1 \dots X_n) = e^{x_1 + \dots + x_n}$.*

Proof. The map $\text{PB}_2 \rightarrow \text{PB}_{n+1}$, $p \mapsto p^{0,1,\dots,n}$ takes x_{01} to $x_{01} \dots x_{0n} = X_1 \dots X_n$. Similarly to (9), one proves that the diagram

$$\begin{array}{ccc} \text{PB}_2 & \xrightarrow{p \mapsto p^{0,1,\dots,n}} & \text{PB}_{n+1} \\ \tilde{\mu}_{\bullet\bullet} \downarrow & & \downarrow \tilde{\mu}_{\bullet \otimes \bar{O}} \\ \exp(\hat{\mathfrak{t}}_2) & \xrightarrow{x \mapsto x^{0,1,\dots,n}} & \exp(\hat{\mathfrak{t}}_{n+1}) \end{array}$$

commutes. \square

The various isomorphisms μ_O are related by the identities

$$(7) \quad \mu_{O'} = \text{Ad}(\Phi_{O,O'}) \circ \mu_O;$$

the automorphisms $\text{Ad}(\Phi_{O,O'})$ are no longer necessarily inner.

$$4. \text{ THE IDENTITY } \mu_{O^{(i)}} = \mu_O^{1,2,\dots,ii+1,\dots,n} \circ \mu_{\bullet(\bullet\bullet)}^{i,i+1}$$

Let $O \in \text{Ob}(\text{PaB})$ be a parenthesized word of length n ; its letters are numbered $0, \dots, n-1$. Let $i \in \{1, \dots, n-1\}$, let $O^{(i)}$ be the object obtained by replacing the letter \bullet numbered i by $(\bullet\bullet)$ (e.g., if $O = \bullet(\bullet\bullet)$, then $O^{(1)} = \bullet((\bullet\bullet)\bullet)$). The purpose of this section is to show the identity

$$\mu_{O^{(i)}} = \mu_O^{1,2,\dots,ii+1,\dots,n} \circ \mu_{\bullet(\bullet\bullet)}^{i,i+1}.$$

4.1. Free magmas and semigroups. Recall that a magma is a triple $(M, M \times M \rightarrow M, e \in M)$ satisfying $e \times m \mapsto m$ and $m \times e \mapsto m$. A semigroup is a magma, where $M \times M \rightarrow M$ is associative.

Let X be a finite set. Let Mg_X be the free magma generated by X and Sg_X the semigroup generated by X . The assignments $X \mapsto \text{Sg}_X$, $X \mapsto \text{Mg}_X$ are functorial and we have a natural

map $Mg_X \rightarrow Sg_X$; so we have a commutative diagram

$$\begin{array}{ccc} Mg_X & \rightarrow & Sg_X \\ \downarrow & & \downarrow \\ Mg_{\{\bullet\}} & \rightarrow & Sg_{\{\bullet\}} = \mathbb{N} \end{array}$$

This diagram is Cartesian, so Mg_X can be identified with a fibered product. Explicitly, we have $Sg_X = \sqcup_{n \geq 0} X^n$, $Mg_{\{\bullet\}} = \sqcup_{n \geq 0} \{\text{parenthesizations of the word } \bullet \dots \bullet \text{ of length } n\} = \sqcup_{n \geq 0} \{\text{rooted planar binary trees with } n \text{ leaves}\}$, $Mg_X = \sqcup_{n \geq 0} \{\text{parenthesized words of length } n \text{ in the alphabet } X\}$.

We denote by $w : Mg_X \rightarrow Sg_X$ (word), $P : Mg_X \rightarrow Mg_{\{\bullet\}}$ (parenthesization) the natural maps; the various maps to \mathbb{N} are denoted by $x \mapsto |x|$ (length).

Note that S_n acts on X^n . For $w, w' \in Sg_X$, with $|w| = |w'| = n$, we then set $S_{w,w'} = \{\sigma \in S_n \mid \sigma \cdot w = w'\}$.

4.2. A braided monoidal category PaB_X . We denote by BMC the ‘category’ of braided monoidal categories (b.m.c.), where morphisms are the tensor functors.

We define a functor $\text{Sets} \rightarrow \text{BMC}$, $X \mapsto \text{PaB}_X$, adjoint to the ‘objects’ functor $\text{BMC} \rightarrow \text{Sets}$, $\mathcal{C} \mapsto \text{Ob}\mathcal{C}$. This means that for any set X and b.m.c. \mathcal{C} , we have a natural bijection $\text{Mor}_{\text{Sets}}(X, \text{Ob}\mathcal{C}) \simeq \text{Mor}_{\text{BMC}}(\text{PaB}_X, \mathcal{C})$. More precisely, we have an injection $X \subset \text{Ob}\text{PaB}_X$, and for any b.m.c. \mathcal{C} and any map $X \rightarrow \text{Ob}\mathcal{C}$, there is attached a tensor functor $\text{PaB}_X \rightarrow \mathcal{C}$, such that $\text{Ob}\text{PaB}_X \rightarrow \text{Ob}\mathcal{C}$ extends $X \rightarrow \text{Ob}\mathcal{C}$. When $X = \{\bullet\}$, PaB_X identifies with Bar-Natan’s PaB .

We now construct PaB_X . We set $\text{Ob}(\text{PaB}_X) := Mg_X$. For $O, O' \in Mg_X$, we set $\text{PaB}_X(O, O') = \emptyset$ if $|O| \neq |O'|$, and $= B_n \times_{\pi} S_{w(O), w(O')}$ if $|O| = |O'| = n$ ($\pi : B_n \rightarrow S_n$ is the canonical projection). So $\text{PaB}_X(O, O') \subset B_n$; since $S_{w,w'}, S_{w',w''} \subset S_{w,w''}$, the product in B_n restricts to a map $\text{PaB}_X(O, O') \times \text{PaB}_X(O', O'') \rightarrow \text{PaB}_X(O, O'')$, which we define as the composition in PaB_X .

The tensor product is defined at the level of objects by the product in Mg_X , and at the level of morphisms is induced by the juxtaposition map $B_n \times B_m \rightarrow B_{n+m}$.

We now construct the braiding and associativity constraints. For $O, O', O'' \in Mg_X$, $a_{O, O', O''} \in \text{PaB}_X((O \otimes O') \otimes O'', O \otimes (O' \otimes O''))$ is defined as the identity element in $B_{n+n'+n''}$ ($n = |O|$, $n' = |O'|$, $n'' = |O''|$).

Then $\beta_{O, O'} \in \text{PaB}_X(O \otimes O', O' \otimes O) \simeq B_{|O|+|O'|}$ corresponds to $\sigma_{n,n'}$ (one checks that the image $s_{n,n'} \in S_{n+n'}$ of $\sigma_{n,n'}$ belongs to the desired $S_{w,w'}$).

One checks that PaB_X , equipped with this structure, is a b.m.c., and that $X \mapsto \text{PaB}_X$ is adjoint to the ‘objects’ functor.

4.3. The category PaCD_X . We first define a tensor category F'_X as follows. $\text{Ob}(F'_X) := Sg_X$, and for $w, w' \in Sg_X$, $F'_X(w, w') = \emptyset$ if $|w| \neq |w'|$, and $= (\exp(\hat{1}_n) \rtimes S_n) \times_{\pi} S_{w,w'}$ else, where $\pi : \exp(\hat{1}_n) \rtimes S_n \rightarrow S_n$ is the canonical projection. The composition is defined as above, using the product in $\exp(\hat{1}_n) \rtimes S_n$, again using $S_{w,w'} S_{w',w''} \subset S_{w,w''}$.

The tensor product is defined, at the level of objects, by the semigroup law, and at the level of morphisms using the juxtaposition $(\exp(\hat{1}_n) \rtimes S_n) \times (\exp(\hat{1}_{n'}) \rtimes S_{n'}) \rightarrow \exp(\hat{1}_{n+n'}) \rtimes S_{n+n'}$.

Let $\Phi \in M_1(\mathbf{k})$. For $X = \{\bullet\}$, $Sg_X = \mathbb{N}$ (we then have $n \otimes m = n + m$). For $n, n', n'' \in \mathbb{N}$, we then set

$$a_{n,n',n''} := \Phi^{1 \dots n, n+1 \dots n+n', n+n'+1 \dots n+n'+n''} \in \exp(\hat{1}_{n+n'+n''}) \in F'_{\{\bullet\}}(n \otimes n' \otimes n'');$$

$s_{n,n'} \in S_{n+n'}$ is the block permutation $i \mapsto n' + i$ ($i \in [n]$), $n + i \mapsto i$ ($i \in [n']$) and

$$\beta_{n,n'} := (e^{t12/2})^{1 \dots n, n+1 \dots n+n'} s_{n,n'} \in \exp(\hat{1}_{n+n'}) \rtimes S_{n+n'} = F'_{\{\bullet\}}(n \otimes n', n' \otimes n).$$

We note that if X is arbitrary and $w, w', w'' \in Sg_X$, then $a_{|w|, |w'|, |w''|} \in F'_X(w \otimes w' \otimes w'')$ and $\beta_{|w|, |w'|} \in F'_X(w \otimes w', w' \otimes w)$.

We define the category \mathbf{PaCD}_X by $\text{Ob}(\mathbf{PaCD}_X) := \text{Mg}_X$, and for $O, O' \in \text{Mg}_X$, we set $\mathbf{PaCD}_X(O, O') := F_X(w(O), w(O'))$. The tensor product is defined at the level of objects as the product in Mg_2 ; as $w : \text{Mg}_2 \rightarrow \text{Sg}_2$ is compatible with products, a tensor product is defined at the level of morphisms by $\mathbf{PaCD}_X(O_1, O_2) \otimes \mathbf{PaCD}_X(O'_1, O'_2) = F_X(w(O_1), w(O_2)) \otimes F_X(w(O'_1), w(O'_2)) \rightarrow F_X(w(O_1) \otimes w(O'_1), w(O_2) \otimes w(O'_2)) = F_X(w(O_1 \otimes O'_1), w(O_2 \otimes O'_2)) = \mathbf{PaCD}_X(O_1 \otimes O'_1, O_2 \otimes O'_2)$.

Let $\Phi \in M_1(\mathbf{k})$. Then Φ gives rise to a b.m.c. structure on \mathbf{PaCD}_X by $a_{O, O', O''} := a_{|O_1|, |O'_1|, |O''_1|} \in F_X(w(O) \otimes w(O') \otimes w(O'')) = \mathbf{PaCD}_X((O \otimes O') \otimes O'', O \otimes (O' \otimes O''))$ and $\beta_{O, O'} := \beta_{|O_1|, |O'_1|} \in F_X(w(O) \otimes w(O'), w(O') \otimes w(O)) = \mathbf{PaCD}_X(O \otimes O', O' \otimes O)$ for $O, O', O'' \in \text{Mg}_X$.

We denote by \mathbf{PaCD}_X^Φ the resulting b.m.c.

4.4. Tensor functors. When $X = X_1 := \{\bullet\}$, \mathbf{PaB}_X coincides with \mathbf{PaB} ; we also denote $\text{Mg}_X, \mathbf{PaCD}_X^\Phi$ by $\text{Mg}, \mathbf{PaCD}^\Phi$. For $X = X_2 := \{\bullet, \circ\}$, we denote $\mathbf{PaB}_X, \mathbf{PaCD}_X^\Phi, \text{Mg}_X, \text{Sg}_X$ by $\mathbf{PaB}_2, \mathbf{PaCD}_2^\Phi, \text{Mg}_2, \text{Sg}_2$.

We define $\mathbf{PaB}_2 \rightarrow \mathbf{PaB}$ as the tensor functor induced by the map $X_2 \rightarrow \text{Mg}_1, \bullet \mapsto \bullet, \circ \mapsto \bullet\bullet$.

We denote by $\mathbf{PaB} \rightarrow \mathbf{PaCD}^\Phi$ the tensor functor induced by the canonical injection $X_1 \rightarrow \text{Ob}(\mathbf{PaCD}^\Phi) = \text{Mg}_1$.

Similarly, we denote by $\mathbf{PaB}_2 \rightarrow \mathbf{PaCD}_2^\Phi$ the tensor functor induced by the canonical injection $X_2 \rightarrow \text{Ob}(\mathbf{PaCD}_2^\Phi) = \text{Mg}_2$.

Let us now construct a functor $F_{X_2} \rightarrow F_{X_1}$. At the level of objects, this is the semigroup morphism $\text{Sg}_2 \rightarrow \text{Sg}_1$ induced by the map $l : X_2 \rightarrow \text{Sg}_1 \simeq \mathbb{N}$, $w \mapsto \tilde{w}$ given by $\bullet \mapsto 1$ and $\circ \mapsto 2$. So for $w = (w_1, \dots, w_n) \in \sqcup_{n \geq 0} X_2^n$, $\tilde{w} = \sum_{i=1}^n l(w_i)$, where $l(\bullet) = 1$ and $l(\bullet\bullet) = 2$. Let us now define the functor at the level of morphisms, i.e. the maps $F_{X_2}(w, w') \rightarrow F_{X_1}(\tilde{w}, \tilde{w}')$. As $F_{X_2}(w, w') = \emptyset$ unless $(\text{card}\{i|w_i = \bullet\}, \text{card}\{i|w_i = \circ\}) = (\text{card}\{i|w'_i = \bullet\}, \text{card}\{i|w'_i = \circ\})$, we will assume that these pairs of integers are equal (in particular $|w| = |w'|$); we denote this pair by (n_1, n_2) . Note that $|w| = |w'| = n_1 + n_2$, while $\tilde{w} = \tilde{w}' = n_1 + 2n_2$.

There is a unique non-decreasing map $\phi_w : [n_1 + 2n_2] \rightarrow [n_1 + n_2]$, such that i has one preimage by ϕ_w if $w_i = \bullet$ and two preimages if $w_i = \circ$; for example, if $w = (\bullet, \bullet, \circ, \circ, \bullet)$, then $\phi_w : [7] \rightarrow [5]$ is $(1, \dots, 7) \mapsto (1, 2, 3, 3, 4, 4, 5)$.

Moreover, for any $\sigma \in S_{n_1+n_2}$, there is a unique $\sigma^w \in S_{n_1+2n_2}$ such that: (a) $\sigma \circ \phi_w = \phi_{w'} \circ \sigma^w$, where $w' = \sigma \cdot w$, so that σ^w restricts to bijections $\phi_w^{-1}(i) \rightarrow \phi_{w'}^{-1}(i)$; (b) these bijections are increasing (this condition is nonempty only if $\text{card}\phi_w^{-1}(i) > 1$). The map $\sigma \mapsto \sigma^w$ is a group morphism $S_{n_1+n_2} \rightarrow S_{n_1+2n_2}$ (it maps a permutation to a block permutation); for example, if $w = (\circ, \bullet, \bullet)$, this map is $S_3 \rightarrow S_4, (\begin{smallmatrix} 1 & 2 & 3 \\ 1 & 2 & 3 \end{smallmatrix}) \mapsto (\begin{smallmatrix} 1 & 2 & 3 & 4 \\ 3 & 1 & 2 & 4 \end{smallmatrix}), (\begin{smallmatrix} 1 & 2 & 3 \\ 1 & 3 & 2 \end{smallmatrix}) \mapsto (\begin{smallmatrix} 1 & 2 & 3 & 4 \\ 1 & 2 & 4 & 3 \end{smallmatrix})$.

The morphisms $\mathfrak{t}_{n_1+n_2} \rightarrow \mathfrak{t}_{n_1+2n_2}, x \mapsto x^{\phi_w}$ and $S_{n_1+n_2} \rightarrow S_{n_1+2n_2}, \sigma \mapsto \sigma^w$ are compatible, so we obtain a group morphism $\exp(\mathfrak{t}_{n_1+n_2}) \times S_{n_1+n_2} \rightarrow \exp(\mathfrak{t}_{n_1+2n_2}) \times S_{n_1+2n_2}$. We then define $F_{X_2}(w, w') \rightarrow F_{X_1}(\tilde{w}, \tilde{w}')$ as the restriction of this group morphism. One checks that this map is compatible with tensor products, so we have defined a tensor functor $F_{X_2} \rightarrow F_{X_1}$.

The tensor functor $F_{X_2} \rightarrow F_{X_1}$ extends to a tensor functor $\mathbf{PaCD}_2^\Phi \rightarrow \mathbf{PaCD}^\Phi$ as follows. There is a unique magma morphism $\text{Mg}_2 \rightarrow \text{Mg}_1, O \mapsto \tilde{O}$, extending the map $X_2 \rightarrow \text{Mg}_1, \bullet \mapsto \bullet, \circ \mapsto \bullet\bullet$. It is such that the diagram

$$\begin{array}{ccc} \text{Mg}_2 & \rightarrow & \text{Mg}_1 \\ \downarrow & & \downarrow \\ \text{Sg}_2 & \rightarrow & \text{Sg}_1 \end{array}$$

commutes. The functor $\mathbf{PaCD}_2^\Phi \rightarrow \mathbf{PaCD}^\Phi$ is defined, at the level of objects, as the map $\text{Mg}_2 \rightarrow \text{Mg}_1$ and at the level of morphisms by $\mathbf{PaCD}_2^\Phi(O, O') = F_{X_2}(w(O), w(O')) \rightarrow F_{X_1}(w(\tilde{O}), w(\tilde{O}')) = F_{X_1}(w(\tilde{O}), w(\tilde{O}')) = \mathbf{PaCD}(O, O')$.

It remains to show that it takes braidings and associativity constraints to their analogues. Namely:

- (a) it takes $\beta_{O,O'} \in \mathbf{PaCD}_2(O \otimes O', O' \otimes O)$ to $\beta_{\tilde{O},\tilde{O}'} \in \mathbf{PaCD}(\tilde{O} \otimes \tilde{O}', \tilde{O}' \otimes \tilde{O})$.
- (b) it takes $a_{O,O',O''} \in \mathbf{PaCD}_2((O \otimes O') \otimes O'', O \otimes (O' \otimes O''))$ to $a_{\tilde{O},\tilde{O}',\tilde{O}''} \in \mathbf{PaCD}((\tilde{O} \otimes \tilde{O}') \otimes \tilde{O}'', \tilde{O} \otimes (\tilde{O}' \otimes \tilde{O}''))$.

To prove (a), let $w, w' = w(O), w(O')$, $(\text{card}\{i|w_i = \bullet\}, \text{card}\{i|w_i = \circ\}) = (n_1, n_2)$, $(\text{card}\{i|w'_i = \bullet\}, \text{card}\{i|w'_i = \circ\}) = (n'_1, n'_2)$. Then $\beta_{O,O'} = \beta_{n_1+n_2, n'_1+n'_2} \in F_{X_2}(w \otimes w', w' \otimes w)$. Similarly, $\beta_{\tilde{O},\tilde{O}'} = \beta_{n_1+2n_2, n'_1+2n'_2} \in F_{X_1}(\tilde{w} \otimes \tilde{w}', \tilde{w}' \otimes \tilde{w})$.

Now note that:

$$((t_{12})^{1\dots n, n+1\dots n+n'})^{\phi_{w \otimes w'}} = (t_{12})^{1\dots n_1+2n_2, n_1+2n_2+1\dots n_1+2n_2+n'_1+2n'_2},$$

and

$$(s_{n,n'})^{w \otimes w'} = s_{n_1+2n_2, n'_1+2n'_2}.$$

So the map $F_{X_2}(w \otimes w', w' \otimes w) \rightarrow F_{X_1}(\tilde{w} \otimes \tilde{w}', \tilde{w}' \otimes \tilde{w})$ takes $\beta_{n,n'}$ to $\beta_{n_1+2n_2, n'_1+2n'_2}$. The proof of (b) is similar.

Then the diagram of functors

$$\begin{array}{ccc} \mathbf{PaB}_2 & \rightarrow & \mathbf{PaB} \\ \downarrow & & \downarrow \\ \mathbf{PaCD}_2^\Phi & \rightarrow & \mathbf{PaCD}^\Phi \end{array}$$

commutes by universal properties (the two composed functors $\mathbf{PaB}_2 \rightarrow \mathbf{PaCD}^\Phi$ coincides as their restrictions to the elements of $X_2 \subset \text{Ob}(\mathbf{PaB}_2)$ do).

Remark 4.1. More generally, to any map $X \rightarrow \text{Mg}_1$, one associates a tensor functor $\mathbf{PaCD}_X^\Phi \rightarrow \mathbf{PaCD}^\Phi$, defined at the level of objects by the extension of this map to a morphism $\text{Mg}_X \rightarrow \text{Mg}_1$ and at the level of morphisms by suitable iterations of cobrackets, and it is such that

$$\begin{array}{ccc} \mathbf{PaB}_X & \rightarrow & \mathbf{PaB} \\ \downarrow & & \downarrow \\ \mathbf{PaCD}_X & \rightarrow & \mathbf{PaCD} \end{array}$$

commutes.

4.5. Relation between braid groups representations. Let $n \geq 1$, let $i \in [n]$, let $w^i = (\bullet, \dots, \bullet, \circ, \bullet, \dots, \bullet) \in \text{Sg}_2$ be given by $w_i = \circ$ and $w_j = \bullet$ for $j \in [n] - \{i\}$. Let $O \in \text{Mg}_2$ be such that $w(O) = w^i$. We have proved that the diagram

$$\begin{array}{ccc} \mathbf{PaB}_2(O) & \rightarrow & \mathbf{PaB}(\tilde{O}) \\ \downarrow & & \downarrow \\ \mathbf{PaCD}_2(O) & \rightarrow & \mathbf{PaCD}(\tilde{O}) \end{array}$$

commutes.

We have isomorphisms:

$\mathbf{PaB}_2(O) \simeq B_n \times_\pi S_{n-1}$, where $S_{n-1} \subset S_n$ identifies with $\{\sigma \in S_n | \sigma(i) = i\}$;

$\mathbf{PaCD}_2(O) \simeq (\exp(\hat{t}_n) \rtimes S_n) \times_\pi S_{n-1}$;

$\mathbf{PaB}(\tilde{O}) \simeq B_{n+1}$;

$\mathbf{PaCD}(\tilde{O}) \simeq \exp(\hat{t}_{n+1}) \rtimes S_{n+1}$.

For $O \in \text{Mg}_{X_1}$, $|O| = n$, the morphism $\mathbf{PaB}(O) \rightarrow \mathbf{PaCD}(O)$ is a morphism $\mu_O : B_n \rightarrow \exp(\hat{t}_n) \rtimes S_n$. Note that if $O_X \in \text{Mg}_X$ and $O := P(O_X)$, then we have a commutative diagram

$$\begin{array}{ccc} \mathbf{PaB}_X(O_X) & \rightarrow & \mathbf{PaCD}_X(O_X) \\ \downarrow & & \downarrow \\ B_n & \xrightarrow{\mu_O} & \exp(\hat{t}_n) \rtimes S_n \end{array}$$

where the vertical maps are injective.

The above commutative diagram therefore inserts in a diagram

$$(8) \quad \begin{array}{ccccc} B_n & \leftarrow & B_n \times_{\pi} S_{n-1} & \xrightarrow{1,2,\dots,\widehat{ii+1},\dots,n} & B_{n+1} \\ \mu_{O \downarrow} & & \downarrow & & \downarrow \mu_{O^{(i)}} \\ \exp(\widehat{f}_n) \rtimes S_n & \leftarrow & (\exp(\widehat{f}_n) \rtimes S_n) \times_{\pi} S_{n-1} & \xrightarrow{1,2,\dots,\widehat{ii+1},\dots,n} & \exp(\widehat{f}_{n+1}) \rtimes S_{n+1} \end{array}$$

Restricting to pure braid groups, we obtain the commutative diagram

$$(9) \quad \begin{array}{ccc} PB_n & \xrightarrow{1,2,\dots,\widehat{ii+1},\dots,n} & PB_{n+1} \\ \mu_{O \downarrow} & & \downarrow \mu_{O^{(i)}} \\ \exp(\widehat{f}_n) & \xrightarrow{1,2,\dots,\widehat{ii+1},\dots,n+1} & \exp(\widehat{f}_{n+1}) \end{array}$$

4.6. Relation between μ_O and $\mu_{O^{(i)}}$. Let $O \in \text{Ob}(\text{PaB})$, $|O| = n$. We index letters in O by $0, \dots, n-1$, fix an index $i \neq 0$ and construct $O^{(i)}$ by doubling inside O the \bullet with index i .

O gives rise to a morphism $\tilde{\mu}_O : B_n \rightarrow \exp(\widehat{f}_n) \rtimes S_n$, which restricts to $\mu_O : F_{n-1} \rightarrow \exp(\widehat{f}_{n-1})$. Similarly, $\tilde{\mu}_{O^{(i)}} : B_{n+1} \rightarrow \exp(\widehat{f}_{n+1}) \rtimes S_{n+1}$ restricts to $\mu_{O^{(i)}} : F_n \rightarrow \exp(\widehat{f}_n)$.

We want to prove that

$$(10) \quad \mu_{O^{(i)}} = \mu_O^{1,2,\dots,\widehat{ii+1},\dots,n} \circ \mu_{\bullet(\bullet\bullet)}^{i,i+1}.$$

We first show that there are uniquely determined elements $g_1, \dots, g_{n-1} \in \exp(\widehat{f}_{n-1})$ and $g, h \in \exp(\widehat{f}_2)$ such that:

(a) $\mu_O = \llbracket g_1(x_1, \dots, x_{n-1}), \dots, g_{n-1}(x_1, \dots, x_{n-1}) \rrbracket$, $\log g_i(x_1, \dots, x_{n-1}) = -\frac{1}{2}(x_1 + \dots + x_{i-1}) + O(x^2)$, and⁸

(b) $\mu_{\bullet(\bullet\bullet)} = \llbracket g(x_1, x_2), h(x_1, x_2) \rrbracket$, $\log g(x_1, x_2) = O(x^2)$, $\log h(x_1, x_2) = -\frac{1}{2}x_1 + O(x^2)$.

Let us prove the first statement (it actually contains the second statement as a particular case). The elements $g_i(x_1, \dots, x_{n-1})$ are uniquely determined by the equality $\mu_O = \llbracket g_1, \dots, g_{n-1} \rrbracket$, together with the condition that the coefficient of x_i in the expansion of $\log g_i$ vanishes. We should then prove that $\log g_i = -\frac{1}{2}(x_1 + \dots + x_{i-1}) + O(x^2)$. We have

$$\tilde{\mu}_O(\sigma_j) = e^{a_j} \cdot e^{t^{j-1,j}/2} s_j \cdot e^{-a_j},$$

where $a_j \in \widehat{f}_n$ has valuation ≥ 2 (we write this as $a_j \in O(t^2)$), and

$$\mu_O(X_i) = \tilde{\mu}_O(\sigma_1)^{-1} \dots \tilde{\mu}_O(\sigma_{i-1})^{-1} \tilde{\mu}_O(\sigma_i)^2 \tilde{\mu}_O(\sigma_{i-1}) \dots \tilde{\mu}_O(\sigma_1).$$

Now

$$\tilde{\mu}_O(\sigma_{i-1}) \dots \tilde{\mu}_O(\sigma_1) = s_{i-1} \dots s_1 e^{\frac{1}{2}(x_1 + \dots + x_{i-1}) + O(t^2)}$$

and $\tilde{\mu}_O(\sigma_i^2) = e^{a_i} e^{t^{i-1,i}} e^{-a_i}$. It follows that

$$\mu_O(X_i) = e^{-\frac{1}{2}(x_1 + \dots + x_{i-1}) + O(t^2)} e^{\tilde{a}_i} \cdot e^{x_i} \cdot (\text{same})^{-1},$$

where $\tilde{a}_i = s_1 \dots s_{i-1} \cdot a_i \cdot s_{i-1} \dots s_1 \in O(t^2)$, so $\mu_O(X_i) = e^{-\frac{1}{2}(x_1 + \dots + x_{i-1}) + O(t^2)} \cdot e^{x_i} \cdot (\text{same})^{-1}$, which implies that g_i has the announced form.

To prove (10), we need to prove the equality

$$(11) \quad \mu_{O^{(i)}} = \llbracket g_1(x_1, \dots, x_i + x_{i+1}, \dots, x_n), \dots, g_i(x_1, \dots, x_i + x_{i+1}, \dots, x_n)g(x_i, x_{i+1}), \\ g_i(x_1, \dots, x_i + x_{i+1}, \dots, x_n)h(x_i, x_{i+1}), \dots, g_{n-1}(x_1, \dots, x_i + x_{i+1}, \dots, x_n) \rrbracket.$$

(9) implies that the diagram

$$\begin{array}{ccc} F_{n-1} & \rightarrow & F_n \\ \mu_{O \downarrow} & & \downarrow \mu_{O^{(i)}} \\ \exp(\widehat{f}_{n-1}) & \rightarrow & \exp(\widehat{f}_n) \end{array}$$

⁸ $O(x^2)$ means an element of \widehat{f}_{n-1} of valuation ≥ 2 .

commutes, where the upper morphism takes X_j ($j \in [n-1]$) to: X_j if $j < i$, $X_i X_{i+1}$ if $j = i$, X_{j+1} if $j > i+1$ and the lower morphism is similarly defined (replacing products by sums and X_k 's by x_k 's). Specializing to the generators X_j ($j \neq i$) of F_{n-1} , this yields

$$\mu_{O^{(i)}}(X_j) = g_j^{0,1,\dots,ii+1,\dots,n} \cdot e^{x_j} \cdot (\text{same})^{-1}$$

for $j < i$ and

$$\mu_{O^{(i)}}(X_j) = g_{j-1}^{0,1,\dots,ii+1,\dots,n} \cdot e^{x_j} \cdot (\text{same})^{-1}$$

for $j > i+1$, which implies that (11) holds when applied to the generators X_j , $j \neq i, i+1$.

We now prove that (11) also holds when applied to X_i and X_{i+1} .

The morphism $X_i \in B_n = \mathbf{PaB}(O, O)$ can be decomposed as

$$O^{(\sigma_{i-2} \dots \sigma_0)^{-1}} (O_1 \otimes (\bullet\bullet)) \otimes O_2 \xrightarrow{\sigma_{i-1}^2} (O_1 \otimes (\bullet\bullet)) \otimes O_2 \xrightarrow{\sigma_{i-2} \dots \sigma_0} O.$$

Here the braid group elements indicate the morphisms. Let $\gamma \in \exp(\mathfrak{t}_n) \rtimes S_n$ be the image of the morphism $O^{(\sigma_{i-2} \dots \sigma_0)^{-1}} (O_1 \otimes (\bullet\bullet)) \otimes O_2$ under $\mathbf{PaB} \rightarrow \mathbf{PaCD}$; its image in S_n is the permutation $s_0 \dots s_{i-2}$, i.e., $(0, \dots, n-1) \mapsto (i-1, 0, 1, \dots, i-2, i, i+1, \dots, n-1)$. The image of $(O_1 \otimes (\bullet\bullet)) \otimes O_2 \xrightarrow{\sigma_{i-1}^2} (O_1 \otimes (\bullet\bullet)) \otimes O_2$ is $e^{t_{i-1,i}}$, therefore the image of X_i is

$$\mu_O(X_i) = \gamma e^{t_{i-1,i}} \gamma^{-1}.$$

We have $\gamma = \gamma_0 s_0 \dots s_{i-2}$, where $\gamma_0 \in \exp(\mathfrak{t}_n)$. As $s_0 \dots s_{i-2} \cdot t_{i-1,i} = x_i$, we have

$$\mu_O(X_i) = \gamma_0 e^{x_i} \gamma_0^{-1}.$$

As this image is also $g_i(x_1, \dots, x_{n-1}) \cdot e^{x_i} \cdot (\text{same})^{-1}$, we derive from this that $g_i^{-1} \gamma_0$ commutes with x_i , hence by Proposition A.1 has the form $e^{\lambda x_i} \alpha^{0i,1,2,\dots,i-1,i+1,\dots,n-1}$, where $\alpha \in \exp(\mathfrak{t}_{n-1})$.

Since $\mu_O(\sigma_j) = s_j e^{t_{j,j+1}/2}$, we get $\log \gamma_0 = -\frac{1}{2}(x_1 + \dots + x_{i-1}) + O(x^2)$. Comparing linear terms in x_i , we get $\lambda = 0$.

Let us now compute $\mu_{O^{(i)}}(X_i)$. The morphism $X_i \in B_{n+1} = \mathbf{PaB}(O^{(i)}, O^{(i)})$ can be decomposed as

$$O^{(i)} (\sigma_{i-2} \dots \sigma_0)^{-1} (O_1 \otimes (\bullet(\bullet\bullet))) \otimes O_2 \xrightarrow{\sigma_{i-1}^2} (O_1 \otimes (\bullet(\bullet\bullet))) \otimes O_2 \xrightarrow{\sigma_{i-2} \dots \sigma_0} O^{(i)}$$

(here σ_{i-1}^2 involves the two first \bullet of $\bullet(\bullet\bullet)$). The morphism $O^{(i)} (\sigma_{i-2} \dots \sigma_0)^{-1} (O_1 \otimes (\bullet(\bullet\bullet))) \otimes O_2$ is obtained from $O^{(i)} (\sigma_{i-2} \dots \sigma_0)^{-1} (O_1 \otimes (\bullet\bullet)) \otimes O_2$ by the operation of doubling of the i th strand, so its image is $\gamma^{0,1,2,\dots,ii+1,\dots,n} = \gamma_0^{0,1,2,\dots,ii+1,\dots,n} (s_0 \dots s_{i-2})$. The image of $\bullet(\bullet\bullet) \xrightarrow{\sigma_{i-1}^2} \bullet(\bullet\bullet)$ is $g(x_1, x_2) \cdot e^{x_1} \cdot (\text{same})^{-1}$, so the image of

$$(O_1 \otimes (\bullet(\bullet\bullet))) \otimes O_2 \xrightarrow{\sigma_{i-1}^2} (O_1 \otimes (\bullet(\bullet\bullet))) \otimes O_2$$

is $g(t_{i-1,i}, t_{i-1,i+1}) e^{t_{i-1,i}} (\text{same})^{-1}$. It follows that

$$\mu_{O^{(i)}}(X_i) = \gamma_0^{0,1,2,\dots,ii+1,\dots,n} g(t_{i-1,i}, t_{i-1,i+1}) e^{t_{i-1,i}} (\text{same})^{-1} = \gamma_0^{0,1,2,\dots,ii+1,\dots,n} g(x_i, x_{i+1}) e^{x_i} \cdot (\text{same})^{-1}.$$

Now we claim that

$$\gamma_0^{0,1,2,\dots,ii+1,\dots,n} g(x_i, x_{i+1}) e^{x_i} (\text{same})^{-1} = g_i^{0,1,2,\dots,ii+1,\dots,n} g(x_i, x_{i+1}) \cdot e^{x_i} \cdot (\text{same})^{-1}.$$

Indeed,

$$\begin{aligned} & (g_i^{-1} \gamma_0)^{0,1,2,\dots,ii+1,\dots,n} g(x_i, x_{i+1}) \cdot e^{x_i} \cdot (\text{same})^{-1} \\ &= (\alpha^{0i,1,2,\dots,i-1,i+1,\dots,n-1})^{0,1,2,\dots,ii+1,\dots,n} g(x_i, x_{i+1}) \cdot e^{x_i} \cdot (\text{same})^{-1} \\ &= \alpha^{0ii+1,2,3,\dots,i-1,i+2,\dots} g(x_i, x_{i+1}) \cdot e^{x_i} \cdot (\text{same})^{-1}. \end{aligned}$$

Now x_i and x_{i+1} commute with any $\alpha^{0ii+1,\dots}$, so this is $g(x_i, x_{i+1}) \cdot e^{x_i} \cdot (\text{same})^{-1}$.

So we get

$$\mu_{O(i)}(X_i) = g_i^{0,1,2,\dots,ii+1,\dots,n} g(x_i, x_{i+1}) \cdot e^{x_i} \cdot (\text{same})^{-1}.$$

The same argument shows that

$$\mu_{O(i)}(X_{i+1}) = g_i^{0,1,2,\dots,ii+1,\dots,n} h(x_i, x_{i+1}) \cdot e^{x_{i+1}} \cdot (\text{same})^{-1},$$

as wanted.

5. THE MAP $M_1(\mathbf{k}) \rightarrow \text{SolKV}(\mathbf{k})$

We show that for $\Phi \in M_1(\mathbf{k})$, $\mu_\Phi \in \text{SolKV}(\mathbf{k})$. By construction of μ_Φ , we have $\mu_\Phi(X) \sim e^x$, $\mu_\Phi(Y) \sim e^y$, so $\mu_\Phi \in \text{TAut}_2$.

5.1. Proof of $\text{Ad } \Phi(t_{12}, t_{23}) \circ \mu_\Phi^{12,3} \circ \mu_\Phi^{1,2} = \mu_\Phi^{1,23} \circ \mu_\Phi^{2,3}$. We first prove:

Proposition 5.1. 1) $\mu_{\bullet(\bullet\bullet)} = \mu_\Phi$.

2) $\Phi_{\bullet((\bullet\bullet)\bullet),\bullet(\bullet(\bullet\bullet))} = \Phi(t_{12}, t_{23})$.

Proof. Let us prove 1). $x_{01} \in B_3 = \text{PaB}(\bullet(\bullet\bullet))$ corresponds to $a_{\bullet,\bullet,\bullet} \circ (\beta_{\bullet,\bullet}^2 \otimes \text{id}_\bullet) \circ a_{\bullet,\bullet,\bullet}^{-1}$. The image of this element in $\exp(\mathfrak{t}_3) \rtimes S_3$ is $\mu_{\bullet(\bullet\bullet)}(X) = \Phi(t_{01}, t_{12}) e^{t_{01}} \Phi(t_{01}, t_{12})^{-1}$. Since $t_{01} + t_{12} + t_{02}$ is central in \mathfrak{t}_3 and since Φ is group-like, this is $\Phi(t_{01}, -t_{01} - t_{02}) e^{t_{01}} \Phi(t_{01}, -t_{01} - t_{02})^{-1} = \Phi(x, -x - y) e^x \Phi(x, -x - y)^{-1} = \mu_\Phi(X)$. Similarly, x_{02} corresponds to $(\text{id}_\bullet \otimes \beta_{\bullet,\bullet}) \circ a_{\bullet,\bullet,\bullet} \circ (\beta_{\bullet,\bullet}^2 \otimes \text{id}_\bullet) \circ a_{\bullet,\bullet,\bullet}^{-1} \circ (\text{id}_\bullet \otimes \beta_{\bullet,\bullet}^{-1})$. The image of this element in $\exp(\mathfrak{t}_3) \rtimes S_3$ is

$$\begin{aligned} \mu_{\bullet(\bullet\bullet)}(Y) &= e^{t_{12}/2} (12) \Phi(t_{01}, t_{12}) e^{t_{01}} \Phi(t_{01}, t_{12})^{-1} (12) e^{-t_{12}/2} = e^{t_{12}/2} \Phi(t_{02}, t_{12}) e^{t_{02}} \Phi(t_{02}, t_{12})^{-1} e^{-t_{12}/2} \\ &= e^{-(t_{01}+t_{02})/2} \Phi(t_{02}, -t_{01} - t_{02}) e^{t_{02}} \Phi(t_{02}, -t_{01} - t_{02})^{-1} e^{(t_{01}+t_{02})/2} \\ &= e^{-(x+y)/2} \Phi(y, -x - y) e^y \Phi(y, -x - y)^{-1} e^{(x+y)/2} = \mu_\Phi(Y). \end{aligned}$$

So $\mu_{\bullet(\bullet\bullet)} = \mu_\Phi$.

Let us now prove 2). Let $O := \bullet((\bullet\bullet)\bullet)$, $O' := \bullet(\bullet(\bullet\bullet))$. Then $\text{can}_{O,O'} = \text{id}_\bullet \otimes a_{\bullet,\bullet,\bullet} \in \text{PaB}(O, O')$, whose image in $\text{PaCD}(O, O') = \exp(\mathfrak{t}_4) \rtimes S_4$ is $\Phi(t_{12}, t_{23}) = \Phi_{O,O'}$. \square

We now prove (2). Applying (4) to $O = \bullet(\bullet\bullet)$ and $i = 1, 2$, and using $\mu_{\bullet(\bullet\bullet)} = \mu_\Phi$, we get

$$\mu_{\bullet((\bullet\bullet)\bullet)} = \mu_\Phi^{12,3} \circ \mu_\Phi^{1,2}, \quad \mu_{\bullet(\bullet(\bullet\bullet))} = \mu_\Phi^{1,23} \circ \mu_\Phi^{2,3}.$$

Moreover, (7) implies

$$\text{Ad } \Phi_{\bullet((\bullet\bullet)\bullet),\bullet(\bullet(\bullet\bullet))} \circ \mu_{\bullet((\bullet\bullet)\bullet)} = \mu_{\bullet(\bullet(\bullet\bullet))}.$$

As $\Phi_{\bullet((\bullet\bullet)\bullet),\bullet(\bullet(\bullet\bullet))} = \Phi(t_{12}, t_{23})$, we get (2).

5.2. Proof of $\mu_\Phi(XY) = e^{x+y}$. We will give three proofs:

First proof. We have

$$\begin{aligned} \mu_\Phi(XY) &= \mu_\Phi(X) \mu_\Phi(Y) \\ &= \Phi(x, -x - y) e^x \Phi(-x - y, x) e^{-(x+y)/2} \Phi(y, -x - y) e^y \Phi(-x - y, x) e^{(x+y)/2} \\ &= \Phi(x, -x - y) e^{x/2} \Phi(y, x) e^{y/2} \Phi(-x - y, x) e^{(x+y)/2} = e^{x+y}, \end{aligned}$$

where the second equality follows from the duality identity and the third and fourth equalities both follow from the hexagon identity.

Second proof. Let us set $\nu := \mu_\Phi^{-1}$. Since μ_Φ satisfies (2), we have

$$(12) \quad \nu^{2,3} \circ \nu^{1,23} = \nu^{1,2} \circ \nu^{12,3} \circ \text{Ad}(\Phi(t_{12}, t_{23})).$$

Let us set $C(x, y) := \nu(x + y)$, and apply (12) to $x + y + z$ to obtain $C(x, C(y, z)) = C(C(x, y), z)$. According to [AT], this implies $C(x, y) = s^{-1} \log(e^{sx} e^{sy})$ for some $s \in \mathbf{k}^\times$. Checking degree 1 and 2 terms in ν , we get $s = 1$.

Third proof. As $\tilde{\mu}_{\bullet\bullet}(x_{01}) = e^{\epsilon^{01}}$, and using Proposition 3.2, we get $\mu_{\bullet\otimes\circ}(X_1\dots X_n) = \tilde{\mu}_{\bullet\otimes\circ}(X_1\dots X_n) = (e^{\epsilon^{01}})^{0,1\dots n} = e^{x_1+\dots+x_n}$. This implies $\mu_\Phi(XY) = e^{x+y}$ since $\mu_\Phi = \mu_{\bullet(\bullet\bullet)}$.

5.3. Proof that $J(\mu_\Phi)$ is a δ -coboundary (end of proof of Theorem 2.1). Since $J(\text{Ad } \Phi(t_{12}, t_{23})) = 0$, and $J(\mu_\Phi^{12,3}) = J(\mu_\Phi)^{12,3}$, etc., we get by applying J to (2),

$$\Phi(t_{12}, t_{23}) \cdot J(\mu_\Phi)^{12,3} + \Phi(t_{12}, t_{23}) \circ \mu_\Phi^{12,3} \cdot J(\mu_\Phi)^{1,2} = J(\mu_\Phi)^{1,23} + \mu_\Phi^{1,23} \cdot J(\mu_\Phi)^{2,3}.$$

Applying the inverse of (2), we get

$$(\mu_\Phi^{1,2})^{-1} \circ (\mu_\Phi^{12,3})^{-1} \cdot J(\mu_\Phi)^{12,3} + (\mu_\Phi^{1,2})^{-1} \cdot J(\mu_\Phi)^{1,2} = (\mu_\Phi^{2,3})^{-1} \circ (\mu_\Phi^{1,23})^{-1} \cdot J(\mu_\Phi)^{1,23} + (\mu_\Phi^{2,3})^{-1} \cdot J(\mu_\Phi)^{2,3},$$

and since $a^{12,3} \cdot t^{12,3} = (a \cdot t)^{12,3}$, etc.,

$$(\mu_\Phi^{1,2})^{-1} \cdot (\mu_\Phi^{-1} \cdot J(\mu_\Phi))^{12,3} + (\mu_\Phi^{-1} \cdot J(\mu_\Phi))^{1,2} = (\mu_\Phi^{2,3})^{-1} \cdot (\mu_\Phi^{-1} \cdot J(\mu_\Phi))^{1,23} + (\mu_\Phi^{-1} \cdot J(\mu_\Phi))^{2,3}.$$

Now $\mu_\Phi^{-1}(x+y) = \log(e^x e^y)$ implies that $(\mu_\Phi^{1,2})^{-1} \cdot t^{12,3} = t^{12,3}$, and similarly with 1, 23, so $\tilde{\delta}(\mu_\Phi^{-1} \cdot J(\mu_\Phi)) = 0$. So there exists $\gamma \in \mathfrak{T}_1$ with valuation ≥ 2 such that $\mu_\Phi^{-1} \cdot J(\mu_\Phi) = \tilde{\delta}(\gamma)$. Now $\mu_\Phi \cdot \gamma^{12} = \gamma^{12}$, and $\mu_\Phi \cdot \gamma^1 = \gamma^1$, $\mu_\Phi \cdot \gamma^2 = \gamma^2$ as $\mu_\Phi(x) \sim x$, $\mu_\Phi(y) \sim y$, therefore $\mu_\Phi \cdot \tilde{\delta}(\gamma) = \delta(\gamma)$. So $J(\mu_\Phi) = \delta(\gamma)$. It follows that for a suitable $\gamma \in u^2\mathbf{k}[[u]]$, we have $J(\mu_\Phi) = \delta(\gamma) = \langle \gamma(x+y) - \gamma(x) - \gamma(y) \rangle$.

All this ends the construction of the map $M_1(\mathbf{k}) \rightarrow \text{SolKV}(\mathbf{k})$, hence the proof of Theorem 2.1.

5.4. Computation of $J(\mu_\Phi)$ (proof of Proposition 2.2). Let $U := [1, A(x, y)] \in \text{TAut}_2$, where

$$\log A(x, y) = \sum_{k \geq 1} \alpha_k (\text{ad } x)^k(y) + O(y^2)$$

(here $O(y^2)$ means a series of elements with y -degree ≥ 2). Then $\log U = \llbracket 0, \sum_{k \geq 1} \alpha_k (\text{ad } x)^k(y) + O(y^2) \rrbracket$, and $J(U) = j(\log U) + O(y^2)$. Now $j(\log U) = \langle \sum_{k \geq 1} \alpha_k y(-x)^k + O(y^2) \rangle$. So

$$J(U) = \langle \sum_{k \geq 1} \alpha_k (-x)^k y \rangle + O(y^2).$$

On the other hand, the hexagon identity implies that $\mu_\Phi = \text{Inn}(\Phi(x, -x-y)e^{-x/2}) \circ \bar{\mu}_\Phi$, where $\bar{\mu}_\Phi = [1, \Phi(x, y)^{-1}]$, and we then have $J(\bar{\mu}_\Phi) = J(\mu_\Phi)$.

We have $\log \Phi(x, y) = -\sum_{k \geq 1} \zeta_\Phi(k+1)(\text{ad } x)^k(y) + O(y^2)$, therefore

$$J(\mu_\Phi) = J(\bar{\mu}_\Phi) = \langle \sum_{k \geq 1} (-1)^k \zeta_\Phi(k+1)x^k y \rangle + O(y^2).$$

As we have $J(\mu_\Phi) = \langle f(x) + f(y) - f(x+y) \rangle$ for some series $f(x)$, we get

$$(13) \quad J(\mu_\Phi) = \langle (-1)^k \frac{\zeta_\Phi(k+1)}{k+1} ((x+y)^{k+1} - x^{k+1} - y^{k+1}) \rangle = \langle \log \Gamma_\Phi(x) + \log \Gamma_\Phi(y) - \log \Gamma_\Phi(x+y) \rangle.$$

This proves Proposition 2.2.

6. GROUP AND TORSOR ASPECTS

6.1. Group structures of $\text{KV}(\mathbf{k})$ and $\text{KRV}(\mathbf{k})$. It is proved in [AT] that $\text{KRV}(\mathbf{k})$ is a group, acting freely and transitively on $\text{SolKV}(\mathbf{k})$.

Let us prove that $\text{KV}(\mathbf{k})$ is a group. For $\alpha \in \text{KV}(\mathbf{k})$, let $\sigma_\alpha := \text{Duf}(\alpha)$, so $\sigma_\alpha \in u^2\mathbf{k}[[u]]$, and $J(\alpha) = \tilde{\delta}(\sigma_\alpha)$. If $\alpha, \alpha' \in \text{KV}(\mathbf{k})$, we have clearly $\alpha' \circ \alpha(X) \sim X$, $\alpha' \circ \alpha(Y) \sim Y$, $\alpha' \circ \alpha(XY) = XY$. Moreover, $J(\alpha' \circ \alpha) = J(\alpha') + \alpha' \cdot J(\alpha) = \tilde{\delta}(\sigma_{\alpha'}) + \alpha' \cdot \tilde{\delta}(\sigma_\alpha) = \tilde{\delta}(\sigma_\alpha + \sigma_{\alpha'})$, where the last equality follows from $\alpha'(X) \sim X$, $\alpha'(Y) \sim Y$, $\alpha'(XY) = XY$, which implies $\tilde{\delta}(\alpha' \cdot t) = \tilde{\delta}(t)$ for $t \in \mathfrak{T}_1$. So $\alpha' \circ \alpha \in \text{KV}(\mathbf{k})$. One proves similarly that $\alpha^{-1} \in \text{KV}(\mathbf{k})$. We have also proved that $\sigma_{\alpha' \circ \alpha} = \sigma_\alpha + \sigma_{\alpha'}$, i.e., $\text{Duf} : \text{KV}(\mathbf{k}) \rightarrow u^2\mathbf{k}[[u]]$ is a group morphism.

6.2. The torsor structure of $\text{SolKV}(\mathbf{k})$ (proof of Proposition 2.3). Let us prove that $\text{KV}(\mathbf{k})$ acts on $\text{SolKV}(\mathbf{k})$. For $\mu \in \text{SolKV}(\mathbf{k})$, let $r_\mu := \text{Duf}(\mu)$, so $r_\mu \in u^2\mathbf{k}[[u]]$, and $J(\mu) = \delta(r_\mu)$. For $\mu \in \text{SolKV}(\mathbf{k})$, $\alpha \in \text{KV}(\mathbf{k})$, we have $\mu \circ \alpha(X) \sim \mu(X) \sim e^x$, $\mu \circ \alpha(Y) \sim \mu(Y) \sim e^y$, $\mu \circ \alpha(XY) = \mu(XY) = e^{x+y}$. Moreover, $J(\mu \circ \alpha) = J(\mu) + \mu \cdot J(\alpha) = \delta(r_\mu) + \mu \cdot \tilde{\delta}(\sigma_\alpha) = \delta(r_\mu + \sigma_\alpha)$, where the last equality uses the identity $\delta(t) = \mu \cdot \tilde{\delta}(t)$ for $t \in \tilde{\mathfrak{T}}_2$, which follows from $\mu(XY) = e^{x+y}$, $\mu(X) \sim e^x$, $\mu(Y) \sim e^y$. So $\mu \circ \alpha \in \text{SolKV}(\mathbf{k})$. We have also proved that $r_{\mu \circ \alpha} = r_\mu + \sigma_\alpha$, so $\text{Duf} : \text{SolKV}(\mathbf{k}) \rightarrow u^2\mathbf{k}[[u]]$ is a morphism of torsors.

Let us now prove that the action of $\text{KV}(\mathbf{k})$ on $\text{SolKV}(\mathbf{k})$ is free and transitive. For $\mu, \mu' \in \text{SolKV}(\mathbf{k})$, set $\alpha := \mu^{-1} \circ \mu'$; then $\alpha(X) \sim X$, $\alpha(Y) \sim Y$, $\alpha(XY) = XY$, and $J(\alpha) = J(\mu^{-1}) + \mu^{-1} \cdot J(\mu') = \mu^{-1} \cdot (J(\mu') - J(\mu))$ as $J(\mu^{-1}) = -\mu^{-1} \cdot J(\mu)$. Then $J(\alpha) = \mu^{-1} \cdot (\delta(r_{\mu'} - r_\mu)) = \tilde{\delta}(r_{\mu'} - r_\mu)$, where the last equality uses $\mu^{-1} \cdot \delta(t) = \tilde{\delta}(t)$ for $t \in \tilde{\mathfrak{T}}_1$. So $\alpha \in \text{KV}(\mathbf{k})$.

6.3. Compatibilities of morphisms with group structures and actions (proof of Theorem 2.5). We now show that: (a) $f \mapsto \alpha_f^{-1}$ is a group morphism $\text{GT}_1(\mathbf{k}) \rightarrow \text{KV}(\mathbf{k})$, (b) $g \mapsto a_g^{-1}$ is a group morphism $\text{GRT}_1(\mathbf{k}) \rightarrow \text{KRV}(\mathbf{k})$, (c) the map $\Phi \mapsto \mu_\Phi$ is compatible with the actions of these groups.

For this, we will show that

$$(14) \quad \mu_{f \star \Phi} = \mu_\Phi \circ \alpha_f, \quad \mu_{\Phi \star g} = a_g \circ \mu_\Phi.$$

We will check these identities on the first generator (X or x), the proofs in the second case being similar.

The proofs go as follows:

$$\begin{aligned} \mu_{f \star \Phi}(X) &= (f \star \Phi)(x, -x - y) \cdot e^x \cdot (\text{same})^{-1} \\ &= f(\Phi(x, -x - y)e^x \Phi(x, -x - y)^{-1}, e^{-x-y}) \Phi(x, -x - y) \cdot e^x \cdot (\text{same})^{-1} \\ &= f(\mu_\Phi(X), \mu_\Phi(Y^{-1}X^{-1})) \cdot \mu_\Phi(X) \cdot (\text{same})^{-1} \\ &= \mu_\Phi(f(X, Y^{-1}X^{-1}) \cdot X \cdot (\text{same})^{-1}) = \mu_\Phi \circ \alpha_f(X) \end{aligned}$$

and

$$\begin{aligned} \mu_{\Phi \star g}(X) &= (\Phi \star g)(x, -x - y) \cdot e^x \cdot (\text{same})^{-1} \\ &= \Phi(g(x, -x - y)xg(x, -x - y)^{-1}, -x - y)g(x, -x - y) \cdot e^x \cdot (\text{same})^{-1} \\ &= \Phi(a_g(x), a_g(-x - y)) \cdot a_g(x) \cdot (\text{same})^{-1} \\ &= a_g(\Phi(x, -x - y)x\Phi(x, -x - y)^{-1}) = a_g \circ \mu_\Phi(X). \end{aligned}$$

The first part of (14) implies the following: (a) if $f \in \text{GT}_1(\mathbf{k})$, then $\alpha_f \in \text{KV}(\mathbf{k})$; (b) $\alpha_{f_1 \star f_2} = \alpha_{f_2} \circ \alpha_{f_1}$; (c) $M_1(\mathbf{k}) \rightarrow \text{SolKV}(\mathbf{k})$ is compatible with the group morphism $f \mapsto \alpha_f^{-1}$.

Indeed, using the nonemptiness of $M_1(\mathbf{k})$ (see [Dr]) we get $\alpha_f = \mu_\Phi^{-1} \circ \mu_{f \star \Phi}$, which implies $\alpha_f \in \text{KV}(\mathbf{k})$ according to Subsection 6.2, i.e., (a). Again using the nonemptiness of $M_1(\mathbf{k})$, we get $\alpha_{f_1 \star f_2} = \mu_\Phi^{-1} \circ \mu_{(f_1 \star f_2) \star \Phi} = (\mu_\Phi^{-1} \circ \mu_{f_2 \star \Phi}) \circ (\mu_{f_1 \star \Phi}^{-1} \circ \mu_{f_1 \star (f_2 \star \Phi)}) = \alpha_{f_2} \circ \alpha_{f_1}$ (where we used $(f_1 \star f_2) \star \Phi = f_1 \star (f_2 \star \Phi)$), which proves (b). (c) is then tautological.

Similarly, the second part of (14) implies: (a) if $g \in \text{GRT}_1(\mathbf{k})$, then $a_g \in \text{KRV}(\mathbf{k})$; (b) $a_{g_1 \star g_2} = a_{g_2} \circ a_{g_1}$; (c) $M_1(\mathbf{k}) \rightarrow \text{SolKV}(\mathbf{k})$ is compatible with the group morphism $g \mapsto a_g^{-1}$. All this proves Theorem 2.5.

It is easy to prove the identities $\alpha_{f_1 * f_2} = \alpha_{f_2} \circ \alpha_{f_1}$, $a_{g_1 * g_2} = a_{g_2} \circ a_{g_1}$ directly (i.e., not using the nonemptiness of $M_1(\mathbf{k})$): the verifications on the first generators (X and x) are

$$\begin{aligned} \alpha_{f_1 * f_2}(X) &= (f_1 * f_2)(X, Y^{-1}X^{-1}) \cdot X \cdot (same)^{-1} \\ &= f_1(f_2(X, Y^{-1}X^{-1})Xf_2(X, Y^{-1}X^{-1})^{-1}, Y^{-1}X^{-1})f_2(X, Y^{-1}X^{-1}) \cdot X \cdot (same)^{-1} \\ &= f_1(\alpha_{f_2}(X), \alpha_{f_2}(Y^{-1}X^{-1})) \cdot \alpha_{f_2}(X) \cdot (same)^{-1} \\ &= \alpha_{f_2}(f_1(X, Y^{-1}X^{-1}) \cdot X \cdot (same)^{-1}) = \alpha_{f_2} \circ \alpha_{f_1}(X), \end{aligned}$$

and

$$\begin{aligned} a_{g_1 * g_2}(x) &= (g_1 * g_2)(x, -x - y) \cdot x \cdot (same)^{-1} \\ &= g_1(g_2(x, -x - y)xg_2(x, -x - y)^{-1}, -x - y)g_2(x, -x - y) \cdot x \cdot (same)^{-1} \\ &= g_1(a_{g_2}(x), a_{g_2}(-x - y)) \cdot a_{g_2}(x) \cdot (same)^{-1} \\ &= a_{g_2}(g_1(x, -x - y)xg_1(x, -x - y)^{-1}) = a_{g_2} \circ a_{g_1}(x). \end{aligned}$$

Remark 6.1. The Lie algebra morphism corresponding to $g \mapsto a_g^{-1}$ is the morphism $\nu : \mathfrak{gt}_1 \rightarrow \mathfrak{fv}$ from [AT], given by $\psi(x, y) \mapsto [\psi(x, -x - y), \psi(y, -x - y)]$.

6.4. Torsor properties of the Dufo formal series (proof of Proposition 2.6). We have already proved that $M_1(\mathbf{k}) \rightarrow \text{SolKV}(\mathbf{k})$, and $\text{SolKV}(\mathbf{k}) \xrightarrow{\text{Duf}} u^2\mathbf{k}[[u]]$ is a morphism of torsors. On the other hand, it follows from [E] that $M_1(\mathbf{k}) \xrightarrow{\Phi \mapsto \log \Gamma_\Phi} \{r \in u^2\mathbf{k}[[u]]\}_{r_{ev}(u) = -\frac{u^2}{24} + \dots}$ is a morphism of torsors and from Proposition 2.2 that the diagram of Proposition 2.6) commutes.

For later use, let us make the group morphism $\text{GT}_1(\mathbf{k}) \rightarrow u^3\mathbf{k}[[u^2]]$ underlying $\Phi \mapsto \log \Gamma_\Phi$ explicit.

Lemma 6.2. For $f \in \text{GT}_1(\mathbf{k})$, there is a unique $\Gamma_f \in \exp(u^3\mathbf{k}[[u^2]])$ such that

$$[\log f(e^a, e^b)] = 1 - \frac{\Gamma_f(-\bar{a})\Gamma_f(-\bar{b})}{\Gamma_f(-\bar{a} - \bar{b})},$$

here we use the isomorphism $\hat{f}'_2/\hat{f}''_2 \simeq \bar{a}\bar{b}\mathbf{k}[[\bar{a}, \bar{b}]]$ given by (class of $(\text{ad } a)^k(\text{ad } b)^l([a, b]) \mapsto \bar{a}^{k+1}\bar{b}^{l+1}$). The map $\text{GT}_1(\mathbf{k}) \rightarrow u^3\mathbf{k}[[u^2]]$, $f \mapsto \log \Gamma_f$ is a group morphism and $\Gamma_{f * \Phi} = \Gamma_f \Gamma_\Phi$ for any $f \in \text{GT}_1(\mathbf{k})$, $\Phi \in M_1(\mathbf{k})$.

Proof. The map $f_2 \rightarrow \mathbf{k}[\bar{a}, \bar{b}]$, $\psi \mapsto (b\partial_b\psi)^{ab}$ also induces an isomorphism $\hat{f}'_2/\hat{f}''_2 \simeq \bar{a}\bar{b}\mathbf{k}[[\bar{a}, \bar{b}]]$, which takes the class $(\text{ad } a)^k(\text{ad } b)^l([a, b])$ to $(-1)^{k+l+1}\bar{a}^{k+1}\bar{b}^{l+1}$. So for $\psi \in \hat{f}'_2$, we have $(b\partial_b\psi)^{ab}(\bar{a}, \bar{b}) = -[\psi](-\bar{a}, -\bar{b})$ (where $\psi \mapsto [\psi]$ is the map $\hat{f}'_2 \rightarrow \hat{f}'_2/\hat{f}''_2 \simeq \bar{a}\bar{b}\mathbf{k}[[\bar{a}, \bar{b}]]$).

So (6) may be rewritten

$$[\log \Phi](\bar{a}, \bar{b}) = 1 - \frac{\Gamma_\Phi(-\bar{a} - \bar{b})}{\Gamma_\Phi(-\bar{a})\Gamma_\Phi(-\bar{b})}.$$

If now $\psi, \alpha \in \hat{f}'_2$, we have $\psi(e^{-\alpha}ae^\alpha, b) \in \hat{f}'_2$ and $[\psi(e^{-\alpha}ae^\alpha, b)] = (1 - [\alpha(a, b)])[\psi(a, b)]$. Indeed, when $\psi(a, b) = (\text{ad } a)^k(\text{ad } b)^l([a, b])$, one checks that the part of $\psi(e^{-\alpha}ae^\alpha, b)$ containing α more than twice lies in \hat{f}''_2 , and the part containing it once has the same class as $(\text{ad } a)^k(\text{ad } b)^l([[-\alpha, a], b])$.

If now $f \in \text{GT}_1(\mathbf{k})$, we have $(f * \Phi)(a, b) = \Phi(a, b)f(\Phi^{-1}(a, b)e^a\Phi(a, b), e^b)$, so

$$\begin{aligned} [\log(f * \Phi)(a, b)] &= [\log \Phi(a, b)] + [\log f(\Phi^{-1}(a, b)e^a\Phi(a, b), e^b)] \\ &= [\log \Phi(a, b)] + [\log f(e^a, e^b)] - [\log \Phi(a, b)][\log f(e^a, e^b)]. \end{aligned}$$

so

$$(15) \quad 1 - [\log(f * \Phi)(a, b)] = (1 - [\log \Phi(a, b)])(1 - [\log f(e^a, e^b)]).$$

If fix $\Phi_0 \in M_1(\mathbf{k})$ and set $\Gamma_f(u) := \Gamma_{f \star \Phi_0}(u) / \Gamma_{\Phi_0}(u)$, then we get

$$1 - [\log f(e^a, e^b)] = \frac{\Gamma_f(-\bar{a})\Gamma_f(-\bar{b})}{\Gamma_f(-\bar{a}-\bar{b})}$$

as wanted. Moreover, (15) implies that $\Gamma_{f \star \Phi} = \Gamma_f \Gamma_\Phi$, which also implies that $f \mapsto \Gamma_f$ is a group morphism. \square

7. DIRECT CONSTRUCTION OF THE MAP $GT_1(\mathbf{k}) \rightarrow KV(\mathbf{k})$

We will now sketch a proof of $(f \in GT_1(\mathbf{k})) \Rightarrow (\alpha_f \in KV(\mathbf{k}))$, independent of the nonemptiness of $M_1(\mathbf{k})$.

7.1. Action of $GT_1(\mathbf{k})$ on completed braid groups. Let \mathcal{C} be a b.m.c. We denote by $\beta_{X,Y} : X \otimes Y \rightarrow Y \otimes X$ and $a_{X,Y,Z} : (X \otimes Y) \otimes Z \rightarrow X \otimes (Y \otimes Z)$ the braiding and associativity constraints. For $O \in \text{Ob}(\mathbf{PaB})$ of length n and any $X_1, \dots, X_n \in \text{Ob}(\mathcal{C})$, we construct the tensor product $O(X_1, \dots, X_n)$ of X_1, \dots, X_n with parenthesization O . We say that \mathcal{C} is prounipotent if for any X_1, \dots, X_n and any O , the image of $\text{PB}_n \rightarrow \text{Aut}_{\mathcal{C}}(O(X_1, \dots, X_n))$ is prounipotent (it suffices to require this for a given O). If \mathcal{C} is a prounipotent b.m.c. and $f \in GT_1(\mathbf{k})$, we construct a new b.m.c. ${}^f\mathcal{C}$ as follows: ${}^f\mathcal{C}$ is the same as \mathcal{C} at the level of objects and morphisms, the composition and the tensor product of morphisms are not modified, but the braiding and associativity constraints are modified as follows:

$$\beta'_{X,Y} = \beta_{X,Y}, \quad a'_{X,Y,Z} = a_{X,Y,Z} \circ f(\beta_{Y,X} \beta_{X,Y}, a_{X,Y,Z}^{-1} \circ \beta_{Z,Y} \beta_{Y,Z} \circ a_{X,Y,Z}).$$

We then have $f_1(f_2\mathcal{C}) = f_1 \star f_2\mathcal{C}$. Moreover, the action of $GT_1(\mathbf{k})$ on BMC is functorial, so a tensor functor $\phi : \mathcal{C} \rightarrow \mathcal{D}$ and $f \in GT_1(\mathbf{k})$ give rise to ${}^f\phi : {}^f\mathcal{C} \rightarrow {}^f\mathcal{D}$. Note that for $O, O' \in \text{Ob}(\mathcal{C})$, and under the identifications ${}^f\mathcal{C}(O, O') = \mathcal{C}(O, O')$, ${}^f\mathcal{D}(\phi(O), \phi(O')) = \mathcal{D}(\phi(O), \phi(O'))$, the map ${}^f\phi(O, O') : {}^f\mathcal{C}(O, O') \rightarrow {}^f\mathcal{D}(\phi(O), \phi(O'))$ coincides with $\phi(O, O') : \mathcal{C}(O, O') \rightarrow \mathcal{D}(\phi(O), \phi(O'))$.

Let $\mathbf{PaB}_{\mathbf{k}}$ be the completion of \mathbf{PaB} obtained by replacing each group B_n by its completion $B_n(S_n, \mathbf{k})$ relative to the morphism $B_n \rightarrow S_n$. By universal properties, we have a unique morphism $\phi_f : \mathbf{PaB} \rightarrow {}^f\mathbf{PaB}$ which is the identity on objects. If then $f_1, f_2 \in GT_1(\mathbf{k})$, we have

$$(16) \quad f_1\phi_{f_2} \circ \phi_{f_1} = \phi_{f_1 \star f_2};$$

indeed, both terms are tensor functors $\mathbf{PaB}_{\mathbf{k}} \rightarrow f_1 \star f_2\mathbf{PaB}_{\mathbf{k}}$ which are the identity on objects.

If now $O \in \text{Ob}(\mathbf{PaB})$ has length n , ϕ_f gives rise to a group morphism $\phi_f(O) : \mathbf{PaB}_{\mathbf{k}}(O) \rightarrow {}^f\mathbf{PaB}_{\mathbf{k}}(O)$. We denote by

$$\tilde{\alpha}_f^O : B_n(S_n, \mathbf{k}) \rightarrow B_n(S_n, \mathbf{k})$$

the group endomorphism derived from $\phi_f(O)$ and the identifications $\mathbf{PaB}_{\mathbf{k}}(O) = {}^f\mathbf{PaB}_{\mathbf{k}}(O) = B_n(S_n, \mathbf{k})$. Identity (16) and the identification of $f_1\tilde{\alpha}_{f_2}^O$ with $\tilde{\alpha}_{f_1 \star f_2}^O$ imply

$$\tilde{\alpha}_{f_2}^O \circ \tilde{\alpha}_{f_1}^O = \tilde{\alpha}_{f_1 \star f_2}^O,$$

so we have a group antimorphism $GT_1(\mathbf{k}) \rightarrow \text{Aut}(B_n(S_n, \mathbf{k}))$, $f \mapsto \tilde{\alpha}_f^O$.

It is easy to see that we have a commutative diagram
$$\begin{array}{ccc} B_n(S_n, \mathbf{k}) & \xrightarrow{\tilde{\alpha}_f^O} & B_n(S_n, \mathbf{k}) \\ & \searrow & \swarrow \\ & S_n & \end{array} \text{ so } \tilde{\alpha}_f^O$$

restricts to an automorphism $\tilde{\alpha}_f^O \in \text{Aut}(\text{PB}_n(\mathbf{k}))$.

If now $O, O' \in \text{Ob}(\mathbf{PaB})$ have length n , then $\text{can}_{O,O'} \in \mathbf{PaB}_{\mathbf{k}}(O, O')$ is the morphism corresponding to the trivial braid. Then $\phi_f(\text{can}_{O,O'}) \circ \text{can}_{O,O'}^{-1} \in \mathbf{PaB}_{\mathbf{k}}(O)$. Let $f^{O,O'} \in \text{PB}_n(\mathbf{k})$

be the image of this element. Since the diagram

$$\begin{array}{ccc} \mathbf{PaB}(O) & \xrightarrow{x \mapsto \text{can}_{O,O'}} \circ \text{cocan}_{O,O'}^{-1} & \mathbf{PaB}(O') \\ & \searrow & \swarrow \\ & \mathbf{B}_n(S_n, \mathbf{k}) & \end{array}$$

commutes, we have

$$(17) \quad \tilde{\alpha}_f^{O'} = \text{Inn}(f^{O,O'}) \circ \tilde{\alpha}_f^O.$$

7.2. Actions of $\text{GT}_1(\mathbf{k})$ on free groups. Let us index the generators of $\text{PB}_n(\mathbf{k})$ by x_{ij} , $0 \leq i < j \leq n-1$. Recall that the subgroup of $\text{PB}_n(\mathbf{k})$ generated by $x_{01}, \dots, x_{0,n-1}$ is isomorphic to $\text{F}_{n-1}(\mathbf{k})$. We set $X_i = x_{0i}$ for $i = 1, \dots, n-1$.

Proposition 7.1. *Each $\tilde{\alpha}_f^O$ restricts to an automorphism $\alpha_f^O \in \text{Aut}(\text{F}_{n-1}(\mathbf{k}))$, such that for any i , $\alpha_f^O(X_i) \sim X_i$.*

Proof. Let us index the letters of O by $0, \dots, n-1$. For $i = 1, \dots, n-1$, let O_i be an object of \mathbf{PaB} of length n , in which the letters $i-1$ and i appear as $\dots(\bullet\bullet)\dots$. We have $X_i = (\sigma_0 \dots \sigma_{i-2})^{-1} \sigma_{i-1}^2 \sigma_0 \dots \sigma_{i-2}$. We have $\tilde{\alpha}_f^O(\sigma_0 \dots \sigma_{i-2}) = \sigma_0 \dots \sigma_{i-2} \cdot p_i$, where $p_i \in \text{PB}_n(\mathbf{k})$. On the other hand, $\tilde{\alpha}_f^O(\sigma_{i-1}) = f^{O,O_i} \tilde{\alpha}_f^O(\sigma_{i-1}) (f^{O,O_i})^{-1}$ and $\tilde{\alpha}_f^O(\sigma_{i-1}) = \sigma_{i-1}$ as $\text{B}_n \simeq \mathbf{PaB}(O_i)$ takes σ_{i-1} to $\text{id}_{\bullet}^{\otimes i-1} \otimes \beta_{\bullet,\bullet} \otimes \text{id}_{\bullet}^{\otimes n-i-2}$. So

$$\tilde{\alpha}_f^O(\sigma_{i-1}) = f^{O,O_i} \sigma_{i-1}^2 (f^{O,O_i})^{-1},$$

with $\alpha_f^{O,O_i} \in \text{PB}_n(\mathbf{k})$. Then

$$(18) \quad \begin{aligned} \tilde{\alpha}_f^O(X_i) &= (\sigma_0 \dots \sigma_{i-2} p_i)^{-1} f^{O,O_i} \sigma_{i-1}^2 (f^{O,O_i})^{-1} \sigma_0 \dots \sigma_{i-2} p_i \\ &= p_i^{-1} (\sigma_0 \dots \sigma_{i-2})^{-1} f^{O,O_i} (\sigma_0 \dots \sigma_{i-2}) \cdot X_i \cdot (\text{same})^{-1}. \end{aligned}$$

As $p_i^{-1} (\sigma_0 \dots \sigma_{i-2})^{-1} f^{O,O_i} (\sigma_0 \dots \sigma_{i-2})$ belongs to $\text{PB}_n(\mathbf{k})$, and as $\text{PB}_n(\mathbf{k})$ acts on $\text{F}_{n-1}(\mathbf{k})$ by tangential automorphisms, we obtain that $\tilde{\alpha}_f^O(X_i)$ lies in $\text{F}_{n-1}(\mathbf{k})$ and is conjugated in $\text{F}_{n-1}(\mathbf{k})$ to X_i . \square

Similarly to Proposition 3.2, one can prove:

Proposition 7.2. *If $O = \bullet \otimes \tilde{O}$, where $\tilde{O} \in \text{Ob}(\mathbf{PaB})$, then $\alpha_f^O(X_1 \dots X_{n-1}) = X_1 \dots X_{n-1}$.*

We then have

$$\alpha_f^{O'} = \text{Ad}(f^{O,O'}) \circ \alpha_f^O;$$

this is an identity in $\text{Aut}(\text{F}_{n-1}(\mathbf{k}))$, where $\text{Ad}(\alpha_f^{O,O'})$ is not necessarily inner.

We also record the identities

$$(19) \quad \tilde{\mu}_{f*\Phi}^O = \tilde{\mu}_\Phi^O \circ \alpha_f^O, \quad \mu_{f*\Phi}^O = \mu_\Phi^O \circ \alpha_f^O.$$

7.3. The map $\text{GT}_1(\mathbf{k}) \rightarrow \text{KV}(\mathbf{k})$. Let us fix an element $f \in \text{GT}_1(\mathbf{k})$ and denote $\tilde{\alpha}_f^O, \alpha_f^O$ simply by $\tilde{\alpha}_O, \alpha_O$.

As in Subsection 4.5, one proves that

$$(20) \quad \begin{array}{ccc} \text{PB}_n(\mathbf{k}) & \xrightarrow{1, 2, \dots, \widetilde{ii+1}, \dots, n} & \text{PB}_{n+1}(\mathbf{k}) \\ \alpha_O \downarrow & & \downarrow \alpha_{O(i)} \\ \text{PB}_n(\mathbf{k}) & \xrightarrow{1, 2, \dots, \widetilde{ii+1}, \dots, n} & \text{PB}_{n+1}(\mathbf{k}) \end{array}$$

commutes. Using Proposition A.3, one then proves

$$(21) \quad \alpha_{O(i)} = \alpha_O^{1, \dots, \widetilde{ii+1}, \dots, n} \circ \alpha_{\bullet(\bullet\bullet)}^{i, i+1}.$$

Similarly to Proposition 5.1, one proves that

- 1) $\alpha_{\bullet(\bullet\bullet)} = \alpha_f$.
- 2) $f_{\bullet((\bullet\bullet)\bullet), \bullet((\bullet\bullet)\bullet)} = f(x_{12}, x_{23})$.

As in Subsection 5.1, one proves that this implies

$$(22) \quad \text{Ad } f(x_{12}, x_{23}) \circ \alpha_f^{\overline{12},3} \circ \alpha_f^{1,2} = \alpha_f^{1,\overline{23}} \circ \alpha_f^{2,3}.$$

As in Subsection 5.2, one can give three proofs of the fact that $\alpha_f(XY) = XY$. Similarly to Subsection 5.3, one then proves that identity (22) then implies that $J(\alpha_f)$ is a $\tilde{\delta}$ -coboundary.

Let us explain this proof in some detail. Since $J(\text{Ad } f(x_{12}, x_{23})) = 0$ and $J(\alpha_f^{\overline{12},3}) = J(\alpha_f)^{\overline{12},3}$, we get by applying J to (22)

$$\text{Ad } f(x_{12}, x_{23}) \cdot J(\alpha_f)^{\overline{12},3} + (\text{Ad } f(x_{12}, x_{23}) \circ \alpha_f^{\overline{12},3}) \cdot J(\alpha_f)^{1,2} = J(\alpha_f)^{\overline{12},3} + J(\alpha_f)^{2,3}.$$

Applying the inverse of (22), we get

$$(\alpha_f^{1,2})^{-1} \cdot (\alpha_f^{-1} \cdot J(\alpha_f))^{\overline{12},3} + (\alpha_f^{-1} \cdot J(\alpha_f))^{1,2} = (\alpha_f^{2,3})^{-1} \cdot (\alpha_f^{-1} \cdot J(\alpha_f))^{1,\overline{23}} + (\alpha_f^{-1} \cdot J(\alpha_f))^{2,3}$$

Now $\alpha_f(XY) = XY$ implies that $\alpha_f^{1,2} \cdot t^{\overline{12},3} = t^{\overline{12},3}$ and similarly with $1, \overline{23}$, so $\tilde{\delta}(\alpha_f^{-1} \cdot J(\alpha_f)) = 0$. As $\hat{\Sigma}_1 \xrightarrow{\tilde{\delta}} \hat{\Sigma}_2 \rightarrow \dots$ is acyclic in degree 2, there exists $\beta \in \hat{\Sigma}_1$ with valuation ≥ 2 such that $\alpha_f^{-1} \cdot J(\alpha_f) = \tilde{\delta}(\beta)$, so $J(\alpha_f) = \alpha_f \cdot \tilde{\delta}(\beta)$. Now $\alpha_f(XY) = XY$, $\alpha_f(X) \sim X$, $\alpha_f(Y) \sim Y$ imply that $\alpha_f \cdot \tilde{\delta}(\beta) = \tilde{\delta}(\beta)$, so $J(\alpha_f) = \tilde{\delta}(\beta)$. It follows that $J(\alpha_f)$ has the form $\tilde{\delta}(\beta) = \langle \beta(\log(e^x e^y)) - \beta(x) - \beta(y) \rangle$.

Remark 7.3. (22) can also be proved directly, checking the identity on each of the generators of $F_3(\mathbf{k})$ and using only the duality, hexagon and pentagon relations. This proof then extends to the profinite and pro- l cases.

8. THE JACOBIANS OF $\mu_{\Phi,O}$ AND α_f^O

8.1. **Telescopic formulas.** If $O \in \text{Ob}(\text{PaB})$ has the form $O = \bullet \otimes O'$, with $|O'| = n$, then one proves by using (4) that μ_O expresses directly in terms of μ_Φ , for example

$$\mu_{\bullet(((\bullet\bullet)(\bullet\bullet))(\bullet\bullet))(\bullet\bullet)} = \mu_\Phi^{1234567,89} \mu_\Phi^{1234,567} \mu_\Phi^{8,9} \mu_\Phi^{12,34} \mu_\Phi^{5,67} \mu_\Phi^{1,2} \mu_\Phi^{3,4} \mu_\Phi^{6,7}.$$

The general formula is

$$\mu_{\bullet \otimes O'} = \prod_{n \geq 0} \prod_{\nu \in N(T'), d(\nu)=n} \mu_\Phi^{L(\nu), R(\nu)};$$

here T' is the binary planar rooted tree underlying O' ; $N(T')$ is the set of its nodes; $d(\nu)$ is the degree of ν (distance to the root of the tree); $L(\nu), R(\nu)$ is the set of left and right leaves of ν (these are disjoint subsets of $\{1, \dots, n\}$). The first product is taken according to increasing values of n (the order in the second product does not matter as the arguments of this product commute with each other). Here is the tree corresponding to the above example (Figure 3):

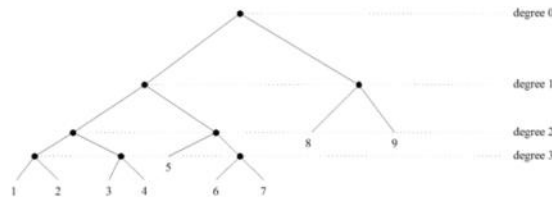


FIGURE 3. There are 8 nodes

Similarly, using (21), one proves that for $f \in \text{GT}_1(\mathbf{k})$, we have

$$\alpha_f^{\bullet \otimes O'} = \prod_{n \geq 0} \prod_{\nu \in N(T'), d(\nu)=n} \alpha_f^{\overline{L(\nu)}, \overline{R(\nu)}}.$$

8.2. **Computation of Jacobians.** Let $\mu_n := \mu_{\bullet(\bullet \dots (\bullet \bullet))}$. Then:

Proposition 8.1. $J(\mu_n) = \langle \sum_{i=1}^n \log \Gamma_{\Phi}(x_i) - \log \Gamma_{\Phi}(\sum_{i=1}^n x_i) \rangle$.

(We identified μ_n with its composition with $e^{x_i} \mapsto X_i$, which belongs to TAut_n .)

Proof. We have $\mu_n = \mu_{\Phi}^{1,2 \dots n} \circ \mu_{\Phi}^{2,3 \dots n} \circ \dots \circ \mu_{\Phi}^{n-1,n}$. One then proves by descending induction on k that $J(\mu_{\Phi}^{k,k+1 \dots n} \circ \dots \circ \mu_{\Phi}^{n-1,n}) = \langle \sum_{i=k}^n \log \Gamma_{\Phi}(x_i) - \log \Gamma_{\Phi}(\sum_{i=k}^n x_i) \rangle$, using the fact that the action of $\mu_{\Phi}^{k,k+1 \dots n}$ on the various $\langle \log \Gamma_{\Phi}(x_i) \rangle$ as well as on $\langle \log \Gamma_{\Phi}(\sum_{i=k}^n x_i) \rangle$ is trivial. \square

If now $O \in \text{Ob}(\text{PaB})$ is arbitrary with $|O| = n + 1$, then:

Proposition 8.2. $J(\mu_{\Phi,O}) = J(\mu_n) = \langle \sum_{i=1}^n \log \Gamma_{\Phi}(x_i) - \log \Gamma_{\Phi}(\sum_{i=1}^n x_i) \rangle$.

Proof. We have $\mu_O = \text{Ad } \Phi_{O_n,O} \circ \mu_n$, where $O_n = \bullet(\dots(\bullet \bullet))$. We then use the cocycle property of J , the above formula for $J(\mu_n)$, the fact that $J(\text{Ad } g) = 0$ for $g \in \exp(\mathfrak{t}_{n+1})$, and the following lemma:

Lemma 8.3. *If $g \in \exp(\mathfrak{t}_{n+1})$, then $(\text{Ad } g)(x_1 + \dots + x_n) \sim x_1 + \dots + x_n$.*

Proof of Lemma. Decompose $a \in \mathfrak{t}_{n+1}$ as $a_0 + a_1^{1,2 \dots n}$, with $a_0 \in \mathfrak{f}_n$ and $a_1 \in \mathfrak{t}_n$ (the map $a_1 \mapsto a_1^{1,2 \dots n}$ is the injection $\mathfrak{t}_n \rightarrow \mathfrak{t}_{n+1}$, $t_{ij} \mapsto t_{ij}$). Then $[t_{ij}, x_1 + \dots + x_n] = 0$ for $i, j \in \{1, \dots, n\}$, so $[a_1^{1,2 \dots n}, x_1 + \dots + x_n] = 0$, so $[a, x_1 + \dots + x_n] = [a_0, x_1 + \dots + x_n]$. It follows that if $g \in \exp(\mathfrak{t}_{n+1})$, there exists $x_g \in \exp(\mathfrak{f}_n)$ such that $(\text{Ad } g)(x_1 + \dots + x_n) = g(x_1 + \dots + x_n)g^{-1}$. \square

We then have:

Proposition 8.4. $J(\alpha_f^O) = \langle \sum_{i=1}^n \log \Gamma_f(\log X_i) - \log \Gamma_f(\log \prod_{i=1}^n X_i) \rangle$.

Proof. Fix $\Phi \in M_1(\mathbf{k})$. We have $\mu_{f \star \Phi}^O = \mu_{\Phi}^O \circ \alpha_f^O$, so $J(\mu_{f \star \Phi}^O) = J(\mu_{\Phi}^O) + \mu_{\Phi}^O \circ J(\alpha_f^O)$. It follows that $\mu_{\Phi}^O \circ J(\alpha_f^O) = \langle \sum_{i=1}^n \log \Gamma_f(x_i) - \log \Gamma_f(\sum_{i=1}^n x_i) \rangle$. The result then follows from $\mu_{f \star \Phi}^O(X_i) \sim e^{x_i}$, $\mu_{\Phi}^O(X_1 \dots X_n) \sim e^{x_1 + \dots + x_n}$. \square

Remark 8.5. In [AT], the Lie subalgebra $\mathfrak{sder}_n \subset \mathfrak{tder}_n$ of special derivations (normalized special in the terms of Ihara) was introduced: $\mathfrak{sder}_n = \{u \in \mathfrak{tder}_n \mid u(x_1 + \dots + x_n) = 0\}$. Let $\tilde{\mathfrak{sder}}_n$ be the intermediate Lie algebra $\tilde{\mathfrak{sder}}_n = \{u \in \mathfrak{tder}_n \mid \exists u_0 \in \mathfrak{f}_{n-1} \mid u(x_1 + \dots + x_n) = [u_0, x_1 + \dots + x_n]\}$ (special derivations in Ihara's terms). So $\mathfrak{sder}_n \subset \tilde{\mathfrak{sder}}_n \subset \mathfrak{tder}_n$. Then Lemma 8.3 says that we have a diagram

$$\begin{array}{ccc} \mathfrak{t}_n & \rightarrow & \mathfrak{sder}_n \\ \downarrow & & \downarrow \\ \mathfrak{t}_{n+1} & \rightarrow & \tilde{\mathfrak{sder}}_n \hookrightarrow \mathfrak{tder}_n \end{array}$$

Remark 8.6. Set $\text{SolKV}_n(\mathbf{k}) := \{\mu_n \in \text{TAut}_n \mid \mu_n(e^{x_1} \dots e^{x_n}) = e^{x_1 + \dots + x_n} \text{ and } \exists r \in u^2 \mathbf{k}[[u]] J(\mu_n) = \langle r(\sum_i x_i) - \sum_i r(x_i) \rangle\}$. This is a torsor under the action of the groups $\text{KV}_n(\mathbf{k}) := \{\alpha_n \in \text{TAut}_n \mid \alpha_n(e^{x_1} \dots e^{x_n}) = e^{x_1} \dots e^{x_n} \text{ and } \exists \sigma \in u^2 \mathbf{k}[[u]] J(\alpha) = \langle \sigma(\log e^{x_1} \dots e^{x_n}) - \sum_i \sigma(x_i) \rangle\}$ and $\text{KRV}_n(\mathbf{k})$ defined similarly (replacing $e^{x_1} \dots e^{x_n}$ by $e^{x_1 + \dots + x_n}$). These are pronilpotent groups; the Lie algebra of $\text{KRV}_n(\mathbf{k})$ is $\mathfrak{trv}_n := \{u \in \mathfrak{tder}_n \mid a(\sum_i x_i) = 0 \text{ and } \exists s \in u^2 \mathbf{k}[[u]] j(a) = \langle s(\sum_i x_i) - \sum_i s(x_i) \rangle\}$. It contains as a Lie subalgebra $\mathfrak{trv}_n^0 := \{a \in \mathfrak{trv}_n \mid s = 0\}$, which is denoted \mathfrak{fv}_n in [AT]. One can prove that if $|O'| = n$ and $O = \bullet \otimes O'$, the map $M_1(\mathbf{k}) \rightarrow \text{SolKV}_n(\mathbf{k})$, $\Phi \mapsto \mu_{\Phi,O}$ is a morphism of torsors.

9. ANALYTIC ASPECTS

In this section, the base field \mathbf{k} is \mathbb{R} or \mathbb{C} .

9.1. Analytic germs. We set $\mathbb{R}_+[[x]] := \{f \in \mathbb{R}_+[[x]] \mid f \text{ has positive radius of convergence}\}$ and $\mathbb{R}_+[[x]]_0 := \{f \in \mathbb{R}_+[[x]] \mid f(0) = 0\}$. If $f, g \in \mathbb{R}_+[[r]]$, we write $f \preceq g$ iff $g - f \in \mathbb{R}_+[[r]]$. We define $f \preceq g$ similarly when $f, g \in \mathbb{R}_+[[r_1, \dots, r_n]]$.

Let V, E be finite dimensional vector spaces and let $|\cdot|_V, |\cdot|_E$ be norms on V, E . The space of E -valued formal series on V is $E[[V]] = \{f = \sum_{n \geq 0} f_n, f_n \in S^n(V^*) \otimes E\}$. For $f_n \in S^n(V^*) \otimes E$, viewed as a homogeneous polynomial $V \rightarrow E$, we set $|f_n| := \sup_{v \neq 0} (|f_n(v)|_E / |v|_V^n)$. An analytic germ on V (at the neighborhood of 0) is a series $f \in E[[V]]$, such that $|f|(r) := \sum_{n \geq 0} |f_n| r^n \in \mathbb{R}_+[[r]]$. We denote by $E\{\{V\}\} \subset E[[V]]$ the subspace of analytic germs, and by $E\{\{V\}\}_0 \subset E[[V]]_0$ the subspace defined by $f_0 = 0$.

If $f \in E\{\{V\}\}$ and $\alpha = \sum_{n \geq 0} \alpha_n r^n \in \mathbb{R}_+[[r]]_0$, we say that α is a dominating series for f if $|f_n| \leq \alpha_n$ for any n ; we write this as $|f(v)|_E \preceq \alpha(|v|_V)$.

If V_1, \dots, V_k are finite dimensional vector spaces with norms $|\cdot|_{V_1}, \dots, |\cdot|_{V_k}$, then we equip $V_1 \oplus \dots \oplus V_k$ with the norm $|(v_1, \dots, v_k)| := \sup_k |v_i|_{V_i}$. If f is an analytic germ $V_1 \oplus \dots \oplus V_k \rightarrow E$, we decompose $f = \sum_{\mathbf{n} \in \mathbb{N}^k} f_{\mathbf{n}}$, where $f_{\mathbf{n}} : V_1 \times \dots \times V_k \rightarrow E$ is the \mathbf{n} -multihomogeneous component of f . We then set

$$|f_{\mathbf{n}}| := \sup_{(x_1, \dots, x_k) \in \prod_i (V_i - \{0\})} |f_{\mathbf{n}}(x_1, \dots, x_k)|_E / |x_1|_{V_1}^{n_1} \dots |x_k|_{V_k}^{n_k}.$$

Then f is an analytic germ iff $|f|(r_1, \dots, r_n) := \sum_{\mathbf{n}} |f_{\mathbf{n}}| r_1^{n_1} \dots r_k^{n_k} \in \mathbb{R}_+[[r_1, \dots, r_k]]$ converges in a polydisc. If $\alpha = \sum_{n_1, \dots, n_k \geq 0} \alpha_{n_1, \dots, n_k} r_1^{n_1} \dots r_k^{n_k} \in \mathbb{R}_+[[r_1, \dots, r_k]]$, we write $|f(v_1, \dots, v_k)|_E \preceq \alpha(|v_1|_{V_1}, \dots, |v_k|_{V_k})$ if for each \mathbf{n} , $|f_{\mathbf{n}}(v_1, \dots, v_k)|_E \leq \alpha_{\mathbf{n}}(|v_1|_{V_1}, \dots, |v_k|_{V_k})$.

Let now \mathfrak{g} be a finite dimensional Lie algebra; let $|\cdot|$ be a norm on \mathfrak{g} ; let $M > 0$ be such that the identity $||[x, y]|| \leq M|x||y|$ holds.

The specialization to \mathfrak{g} of the Campbell–Baker–Hausdorff series is a series $x * y = \text{cbh}(x, y) \in \mathfrak{g}[[\mathfrak{g} \times \mathfrak{g}]]_0$.

Lemma 9.1. 1) The CBH series is an analytic germ $\mathfrak{g} \times \mathfrak{g} \rightarrow \mathfrak{g}$; we have $|x * y| \preceq \frac{1}{M} f(M(|x| + |y|))$, where $f(u) = \int_0^u -\frac{\ln(2-e^{-v})}{v} dv$.

2) $\mathfrak{g} \times \mathfrak{g} \rightarrow \mathfrak{g}$, $(x, y) \mapsto e^{\text{ad } x}(y)$ is an analytic germ, and $|e^{\text{ad } x}(y)| \preceq e^{M|x|}|y|$.

Proof. 1) is proved as in [Bk], not making use of the final majorization $\frac{1}{r+s} \leq 1$. Using Dynkin's formula, one can prove that 2) follows from $|(\text{ad } x)^n(y)| \leq M^n |x|^n |y|$. \square

9.2. $\text{TAut}_n^{an}(\mathfrak{g})$ and $\text{Idet}_n^{an}(\mathfrak{g})$. We set $\text{TAut}_n(\mathfrak{g}) := \{(a_1, \dots, a_n) \mid a_i \in \mathfrak{g}[[\mathfrak{g}^n]]_0\}$ and define on this set a product by $(a_1, \dots, a_n)(b_1, \dots, b_n) := (c_1, \dots, c_n)$, where

$$c_i(x_1, \dots, x_n) := b_i(e^{\text{ad } a_1(x_1, \dots, x_n)}(x_1), \dots, e^{\text{ad } a_n(x_1, \dots, x_n)}(x_n)) * a_i(x_1, \dots, x_n).$$

This equips $\text{TAut}_n(\mathfrak{g})$ with a group structure. We set $\text{TAut}_n^{an}(\mathfrak{g}) := \{(a_1, \dots, a_n) \mid a_i \in \mathfrak{g}\{\{\mathfrak{g}^n\}\}_0\}$.

Proposition 9.2. $\text{TAut}_n^{an}(\mathfrak{g})$ is a subgroup of $\text{TAut}_n(\mathfrak{g})$.

Proof. Let (a_1, \dots, a_n) and (b_1, \dots, b_n) belong to $\text{TAut}_n^{an}(\mathfrak{g})$. Let $\alpha(r), \beta(r) \in \mathbb{R}_+[[r]]_0$ be germs such that the identities $|a_i(x_1, \dots, x_n)| \preceq \alpha(\sup_i |x_i|)$, $|b_i(x_1, \dots, x_n)| \preceq \beta(\sup_i |x_i|)$ hold. Then

$$\begin{aligned} |c_i(x_1, \dots, x_n)| &\preceq f_M(|a_i(x_1, \dots, x_n)| + |b_i(e^{\text{ad } a_1(x_1, \dots, x_n)}(x_1), \dots, e^{\text{ad } a_n(x_1, \dots, x_n)}(x_n))|) \\ &\preceq f_M(\alpha(\sup_i |x_i|) + \beta(e^{M\alpha(\sup_i |x_i|)} \sup_i |x_i|)) = \gamma(\sup_i |x_i|), \end{aligned}$$

where $f_M(u) = \frac{1}{M} f(Mu)$ and $\gamma(r) = f_M(\alpha(r) + e^{M\alpha(r)}\beta(r))$ has nonzero radius of convergence. Here we use the compatibility of norms with composition: namely, if $f \in E[[V_1 \times \dots \times V_n]]_0$ and $g_i \in V_i[[W]]_0$, with $|f(v_1, \dots, v_n)| \preceq \alpha(|v_1|, \dots, |v_n|)$ and $|g_i(w)| \preceq \beta_i(|w|)$, then $h := f \in (g_1, \dots, g_n) \in E[[W]]_0$ and $|h(w)| \preceq \alpha \circ (\beta_1, \dots, \beta_n)(|w|)$. We also use the

non-decreasing properties of elements of $\mathbb{R}_+[[r_1, \dots, r_n]]_0$ (i.e., if $F \in \mathbb{R}_+[[u_1, \dots, u_k]]_0$ and $u_i, u'_i \in \mathbb{R}_+[[r_1, \dots, r_l]]_0$ with $u_i \preceq u'_i$, then $F(u_1, \dots) \preceq F(u'_1, \dots)$). So $(a_1, \dots, a_n)(b_1, \dots, b_n) \in \text{TAut}_n^{\text{an}}(\mathfrak{g})$.

If now $(a_1, \dots, a_n) \in \text{TAut}_n^{\text{an}}(\mathfrak{g})$, then its inverse (b_1, \dots, b_n) in $\text{TAut}_n(\mathfrak{g})$ is uniquely determined by the identities

$$b_i(x_1, \dots, x_n) = -a_i(e^{\text{ad } b_1(x_1, \dots, x_n)}(x_1), \dots, e^{\text{ad } b_n(x_1, \dots, x_n)}(x_n)).$$

Let us show that each $b_i(x_1, \dots, x_n)$ is an analytic germ. For this, we define inductively the sequence $b^{(k)} = (b_1^{(k)}, \dots, b_n^{(k)})$ by $b^{(0)} = (0, \dots, 0)$, and

$$b_i^{(k+1)}(x_1, \dots, x_n) = -a_i(e^{\text{ad } b_1^{(k)}(x_1, \dots, x_n)}(x_1), \dots, e^{\text{ad } b_n^{(k)}(x_1, \dots, x_n)}(x_n)).$$

One checks that $b^{(k)} = b^{(k-1)} + O(x^k)$, so the sequence $(b^{(k)})_{k \geq 0}$ converges in the formal series topology; the limit b is then the inverse of $a = (a_1, \dots, a_n)$.

Let us now set $\beta_k := \sup_i |b_i^{(k)}|$ (if $u_i(r) = \sum_{k \geq 0} u_{i,k} r^k \in \mathbb{R}_+[[r]]$ is a finite family, we set $(\sup_i u_i)(r) := \sum_{k \geq 0} (\sup_i u_{i,k}) r^k$). We then have

$$|b_i^{(k+1)}(x_1, \dots, x_n)| \preceq \alpha(\sup_i |e^{\text{ad } b_i^{(k)}(x_1, \dots, x_n)}(x_i)|) \preceq \alpha(e^{M\beta_k(\sup_i |x_i|)} \sup_i |x_i|),$$

so $\beta_{k+1}(r) \preceq \alpha(e^{\beta_k(r)r})$.

We now define a sequence $(\gamma_k)_{k \geq 0}$ of elements of $\mathbb{R}_+[[r]]_0$ by $\gamma_0 = 0$,

$$\gamma_{k+1}(r) = \alpha(e^{M\gamma_k(r)r}).$$

As the exponential function, multiplication by r and α are non-decreasing, we have $\beta_k \preceq \gamma_k$. On the other hand, we have $\gamma_k(r) = \gamma_{k-1}(r) + O(r^k)$, so the sequence $(\gamma_k)_k$ converges in $\mathbb{R}_+[[r]]_0$ (one also checks that this sequence is non-decreasing). Its limit γ then satisfies

$$(23) \quad \gamma(r) = \alpha(e^{M\gamma(r)r}).$$

It is easy to show that (23) determines $\gamma(r) \in \mathbb{R}[[r]]_0$ uniquely. On the other hand, the function $(\gamma, r) \mapsto \gamma - \alpha(e^{M\gamma r}) =: F(\gamma, r)$ is analytic at the neighborhood of $(0, 0)$, with differential at this point $\partial_r F(0, 0)d\gamma + \partial_\gamma F(0, 0)dr = d\gamma - M\alpha'(0)dr$. We may then apply the implicit function theorem and use the fact that the $d\gamma$ -component of $dF(0, 0)$ is nonzero to derive the existence of an analytic function $\gamma_{\text{an}}(r)$ satisfying (23). By the uniqueness of solutions of (23), we get that the expansion of γ_{an} is γ , so $\gamma \in \mathbb{R}_+\{\{r\}\}_0$.

Now $|b_i^{(k)}(x_1, \dots, x_n)| \preceq \beta_k(\sup_i |x_i|) \preceq \gamma_k(\sup_i |x_i|) \preceq \gamma(\sup_i |x_i|)$, so by taking the limit $k \rightarrow \infty$, $|b_i(x_1, \dots, x_k)| \preceq \gamma(\sup_i |x_i|)$, which implies that $b_i \in \mathfrak{g}\{\{\mathfrak{g}^n\}\}_0$, as wanted. \square

According to [AT], we have a bijection

$$\kappa : \text{TAut}_n \rightarrow \text{tder}_n, \quad g \mapsto \ell - g\ell g^{-1},$$

where ℓ is the derivation given by $x_i \mapsto x_i$.

Set $\text{tder}_n(\mathfrak{g}) := \{(u_1, \dots, u_n) | u_i(x_1, \dots, x_n) \in \mathfrak{g}[[\mathfrak{g}^n]]_0\}$, and $\text{tder}_n^{\text{an}}(\mathfrak{g}) := \{(u_1, \dots, u_n) | u_i \in \mathfrak{g}\{\{\mathfrak{g}^n\}\}_0\} \subset \text{tder}_n(\mathfrak{g})$. We have maps $\text{TAut}_n \rightarrow \text{TAut}_n(\mathfrak{g})$, $\text{tder}_n \rightarrow \text{tder}_n(\mathfrak{g})$ induced by the specialization of formal series.

Lemma 9.3. 1) *There exists a map $\kappa_{\mathfrak{g}} : \text{TAut}_n(\mathfrak{g}) \rightarrow \text{tder}_n(\mathfrak{g})$, such that the diagram*

$$\begin{array}{ccc} \text{TAut}_n & \xrightarrow{\kappa} & \text{tder}_n \\ \downarrow & & \downarrow \\ \text{TAut}_n(\mathfrak{g}) & \xrightarrow{\kappa_{\mathfrak{g}}} & \text{tder}_n(\mathfrak{g}) \end{array}$$

commutes.

2) *This map restricts to a map $\kappa_{\mathfrak{g}}^{\text{an}} : \text{TAut}_n^{\text{an}}(\mathfrak{g}) \rightarrow \text{tder}_n^{\text{an}}(\mathfrak{g})$.*

Proof. 1) If $a_i, b_i \in \hat{\mathfrak{f}}_n$ are such that $g = [e^{b_1}, \dots, e^{b_n}]$, $g^{-1} = [e^{a_1}, \dots, e^{a_n}]$, then $\kappa(g) = u = [u_1, \dots, u_n]$, with

$$u_i(x_1, \dots, x_n) = \left(\frac{1 - e^{\text{ad } a_i}}{\text{ad } a_i}(\hat{a}_i) \right) (e^{\text{ad } b_1(x_1, \dots, x_n)}(x_1), \dots, e^{\text{ad } b_n(x_1, \dots, x_n)}(x_n))$$

and $\hat{a}_i = \ell(a_i) = \frac{d}{dt}|_{t=1} a_i(t x_1, \dots, t x_n)$. So we define $\kappa_{\mathfrak{g}}$ by the same formula, where \hat{a}_i is now defined as $\frac{d}{dt}|_{t=1} a_i(t x_1, \dots, t x_n)$ (or $\sum_{k \geq 0} k a_i^k$, where a_i^k is the degree n part of a_i).

2) If the functions a_i, b_i are analytic germs, then so is \hat{a}_i and therefore also each u_i . \square

Recall also from [AT] that if $\mu \in \text{TAut}_2$, $\mu(x * y) = x + y$ and $J(\mu) = \langle r(x) + r(y) - r(x + y) \rangle$ (i.e., $\mu \in \text{SolKV}(\mathbf{k})$), then $u := -\kappa(\mu^{-1}) = [A(x, y), B(x, y)]$ satisfies:

$$\text{(KV1)} \quad x + y - y * x = (1 - e^{-\text{ad } x})(A(x, y)) + (e^{\text{ad } y} - 1)(B(x, y)),$$

$$\text{(KV3)} \quad j(u) = \langle \phi(x) + \phi(y) - \phi(x * y) \rangle, \text{ where } \phi(t) = t r'(t).$$

Let Φ_{KZ} be the KZ associator, $\tilde{\Phi}_{\text{KZ}}(a, b) := \Phi_{\text{KZ}}(a/(2\pi i), b/(2\pi i)) \in M_1(\mathbb{C})$ and $\mu_{\text{KZ}} := \mu_{\tilde{\Phi}_{\text{KZ}}}$. Let $u_{\text{KZ}} := \kappa(\mu_{\text{KZ}}^{-1})$. Then $J(\mu_{\text{KZ}}) = \langle r_{\text{KZ}}(x) + r_{\text{KZ}}(y) - r_{\text{KZ}}(x * y) \rangle$, where $r_{\text{KZ}}(u) = -\sum_{n \geq 2} (2\pi i)^{-n} \zeta(n) u^n / n$, therefore

$$j(u_{\text{KZ}}) = \langle \phi_{\text{KZ}}(x) + \phi_{\text{KZ}}(y) - \phi_{\text{KZ}}(x * y) \rangle,$$

where $\phi_{\text{KZ}}(u) = -\sum_{n \geq 2} (2\pi i)^{-n} \zeta(n) u^n$. Now the real part of this function (obtained by taking the real part of the coefficients of u^n) is

$$\phi_{\text{KZ}}^{\mathbb{R}}(u) = \frac{1}{2} \left(\frac{u}{e^u - 1} - 1 + \frac{u}{2} \right).$$

Let us now set $u_{\mathbb{R}} := [A_{\mathbb{R}}(x, y), B_{\mathbb{R}}(x, y)]$, where the real part is taken with respect to the natural real structure on $\hat{\mathfrak{f}}_2$. Then by the linearity of (KV1), (KV3), we have:

$$\text{(KV1)} \quad x + y - y * x = (1 - e^{-\text{ad } x})(A_{\mathbb{R}}(x, y)) + (e^{\text{ad } y} - 1)(B_{\mathbb{R}}(x, y))$$

$$\text{(KV3)} \quad j(u_{\mathbb{R}}) = \frac{1}{2} \left(\frac{x}{e^x - 1} + \frac{y}{e^y - 1} - \frac{x * y}{e^{x * y} - 1} - 1 \right).$$

9.3. Analytic aspects to the KV conjecture (proof of Theorem 2.8). Recall that $\log \tilde{\Phi}_{\text{KZ}} \in \hat{\mathfrak{f}}_2$. We denote the specialization of this series to the Lie algebra \mathfrak{g} as $(\log \tilde{\Phi}_{\text{KZ}})^{\mathfrak{g}} \in \mathfrak{g}[[\mathfrak{g}^2]]_0$.

Proposition 9.4. *($\log \tilde{\Phi}_{\text{KZ}})^{\mathfrak{g}}$ is an analytic germ, i.e., $(\log \tilde{\Phi}_{\text{KZ}})^{\mathfrak{g}} \in \mathfrak{g}\{\{\mathfrak{g}^2\}\}_0$.*

Proof. Recall that $A_2 = U(\mathfrak{f}_2)$ is the free associative algebra in a, b . For $x \in A_2$, set

$$|x|_{A_2} := \sup_{N \geq 1} \sup_{m_1, m_2 \in M_N(\mathbb{C})} \|x(m_1, m_2)\|.$$

Here $\|\cdot\|$ is an algebra norm on $M_N(\mathbb{C})$. Then $|x|_{A_2}$ is $\leq \sum_{I \in \cup_{n \geq 0} \{0, 1\}^n} |x_I|$, where $x = \sum_I x_I e_I$, and for $I = (i_1, \dots, i_n)$, $e_I = e_{i_1} \dots e_{i_n}$, $e_0 = a$, $e_1 = b$. It follows from the Amitsur–Levitsky theorem ([AL]) that $(|x|_{A_2} = 0) \Rightarrow (x = 0)$; indeed, by this theorem, $x(m_1, m_2) = 0$ for $m_1, m_2 \in M_N(\mathbb{C})$ implies: (a) that x is in the 2-sided ideal generated by $ab - ba$ if $N = 1$; (b) that $x = 0$ if $N > 1$. It follows that $|\cdot|_{A_2}$ is an algebra norm⁹ on A_2 , in particular $|xy|_{A_2} \leq |x|_{A_2} |y|_{A_2}$.

We then define a vector space norm $|\cdot|_{\mathfrak{f}_2}$ on \mathfrak{f}_2 by $|x|_{\mathfrak{f}_2} := |x|_{A_2}$; we have $|[x, y]|_{\mathfrak{f}_2} \leq 2|x|_{\mathfrak{f}_2} |y|_{\mathfrak{f}_2}$.

For $\mathbf{n} = (n_1, \dots, n_d) \in \mathbb{N}^d$, and f a function on $(\mathfrak{f}_2)^d$ (resp., \mathbb{R}^d), we denote by $f(\xi_1, \dots, \xi_d)_{\mathbf{n}}$ (resp., $f(t_1, \dots, t_d)_{\mathbf{n}}$) the \mathbf{n} -multihomogeneous part of f , which we view as a multihomogeneous polynomial on $(\mathfrak{f}_2)^d$ (resp., \mathbb{R}^d).

Lemma 9.5. *For any \mathbf{n} , we have the identity*

$$|\log(e^{\xi_1} \dots e^{\xi_d})_{\mathbf{n}}|_{\mathfrak{f}_2} \leq ((\log(2 - e^{t_1 + \dots + t_d})^{-1})_{\mathbf{n}})_{t_1=|\xi_1|_{\mathfrak{f}_2}, \dots, t_d=|\xi_d|_{\mathfrak{f}_2}}.$$

⁹We will not use $(|x|_{A_2} = 0) \Rightarrow (x = 0)$, so our proof is independent of the Amitsur–Levitsky theorem.

Proof of Lemma. We have for any \mathbf{n} , $|\xi_1^{n_1} \dots \xi_d^{n_d}|_{A_2} \leq |\xi_1|_{f_2}^{n_1} \dots |\xi_d|_{f_2}^{n_d}$ so

$$|(e^{\xi_1} \dots e^{\xi_d} - 1)_{\mathbf{n}}|_{A_2} \leq ((e^{t_1+\dots+t_d} - 1)_{\mathbf{n}})_{t_1=|\xi_1|_{f_2}, \dots, t_d=|\xi_d|_{f_2}}.$$

Then $\log(e^{\xi_1} \dots e^{\xi_d})_{\mathbf{n}} = \sum_{k \geq 1} \frac{(-1)^{k+1}}{k} \sum_{(\mathbf{n}_1, \dots, \mathbf{n}_k) | \mathbf{n}_1 + \dots + \mathbf{n}_k = \mathbf{n}} (e^{\xi_1} \dots e^{\xi_d} - 1)_{\mathbf{n}_1} \dots (e^{\xi_1} \dots e^{\xi_d} - 1)_{\mathbf{n}_k}$ so

$$\begin{aligned} |\log(e^{\xi_1} \dots e^{\xi_d})_{\mathbf{n}}|_{A_2} &\leq \left(\sum_{k \geq 1} \frac{1}{k} \sum_{\mathbf{n}_1 + \dots + \mathbf{n}_k = \mathbf{n}} (e^{t_1+\dots+t_d} - 1)_{\mathbf{n}_1} \dots (e^{t_1+\dots+t_d} - 1)_{\mathbf{n}_k} \right)_{t_1=|\xi_1|_{f_2}, \dots, t_d=|\xi_d|_{f_2}} \\ &= \left(\sum_{k \geq 1} \frac{1}{k} ((e^{t_1+\dots+t_d} - 1)^k)_{\mathbf{n}} \right)_{t_1=|\xi_1|_{f_2}, \dots, t_d=|\xi_d|_{f_2}} = ((\log(2 - e^{t_1+\dots+t_d})^{-1})_{\mathbf{n}})_{t_1=|\xi_1|_{f_2}, \dots, t_d=|\xi_d|_{f_2}}. \end{aligned}$$

□

Let $a(t)$ be an function $[0, 1] \rightarrow \hat{f}_2$ of the form $a(t) = \sum_{k \geq 1} a_k(t)$, where $a_k(t) \in f_2[k]$ (here k is the total degree in a, b) and $\int_0^1 |a_k(t)|_{f_2} dt < \infty$. Let u_0, u_1 be solutions of $u'(t) = a(t)u(t)$ with $u_0(0) = u_1(1) = 1$, and $U := u_1^{-1}u_0$.

Lemma 9.6. For $n \geq 1$, let $(\log U)_n$ the degree n (in a, b) part of $\log U$. Then

$$\sum_{n \geq 1} |(\log U)_n|_{f_2} r^n \leq \log(2 - e^{\sum_{k \geq 1} r^k \int_0^1 |a_k(t)|_{f_2} dt})^{-1}.$$

Proof of Lemma. Let $\text{Lie}(n)$ be the multilinear part of f_n in the generators x_1, \dots, x_n . We denote by $w_n(x_1, \dots, x_n) \in \text{Lie}(n)$ the multilinear part of $\log(e^{x_1} \dots e^{x_n})$.

Let now α_n be the coefficient of $t_1 \dots t_n$ in the expansion of $\log(2 - e^{t_1+\dots+t_n})^{-1}$ (this is also the n th derivative at $t = 0$ of $\log(2 - e^t)^{-1}$). Specializing Lemma 9.5 for $\mathbf{n} = (1, \dots, 1)$, we get the identity

$$|w_n(\xi_1, \dots, \xi_n)|_{f_2} \leq \alpha_n |\xi_1|_{f_2} \dots |\xi_n|_{f_2}$$

for $\xi_1, \dots, \xi_n \in f_2$.

Now $\log U$ expands as

$$\log U = \sum_{n \geq 0} \int_{0 < t_1 < \dots < t_n < 1} w_n(a(t_1), \dots, a(t_n)) dt_1 \dots dt_n$$

(see e.g. [EG]). It follows that

$$(\log U)_k = \sum_{n \geq 0} \sum_{k_1, \dots, k_n | \sum_i k_i = k} \int_{0 < t_1 < \dots < t_n < 1} w_n(a_{k_1}(t_1), \dots, a_{k_n}(t_n)) dt_1 \dots dt_n$$

and therefore

$$|(\log U)_k|_{f_2} \leq \sum_{n \geq 0} \alpha_n \sum_{k_1, \dots, k_n | \sum_i k_i = k} \int_{0 < t_1 < \dots < t_n < 1} |a_{k_1}(t_1)|_{f_2} \dots |a_{k_n}(t_n)|_{f_2} dt_1 \dots dt_n.$$

Now the generating series for the r.h.s. is $\log(2 - e^{\sum_{k \geq 1} r^k \int_0^1 |a_k(t)|_{f_2} dt})^{-1}$, proving the result. □

According to [Dr], Section 2, if we set

$$a(t) := \sum_{k \geq 0, l \geq 1} \frac{1}{k!l!(2\pi i)^{k+l+1}} \frac{(-\log(1-t))^k (-\log t)^l}{t-1} (\text{ad } b)^k (\text{ad } a)^l(b),$$

then $\hat{\Phi}_{KZ} = U$. We have $|(\text{ad } b)^k (\text{ad } a)^l(b)|_{f_2} \leq k + l + 2 \leq 2^{k+l+1}$, so

$$|a_n(t)| \leq \sum_{k \geq 0, l \geq 1, k+l+1=n} \frac{1}{\pi^{k+l+1} k!l!} \frac{(-\log(1-t))^k (-\log t)^l}{1-t}$$

Then we have the inequality of formal series in r

$$\begin{aligned} \sum_{n \geq 1} r^n \int_0^1 |a_n(t)|_{f_2} dt &\leq \int_0^1 \sum_{k \geq 0, l \geq 1} \frac{r^{k+l+1}}{\pi^{k+l+1} k! l!} \frac{(-\log(1-t))^k (-\log t)^l}{1-t} dt \\ &= \frac{r}{\pi} \int_0^1 (1-t)^{-1-\frac{r}{\pi}} (t^{-\frac{r}{\pi}} - 1) dt. \end{aligned}$$

Now the identity $\int_0^1 t^a (1-t)^b dt = \frac{\Gamma(a+1)\Gamma(b+1)}{\Gamma(a+b+2)}$, valid for $\Re(a), \Re(b) > -1$, implies that if $\Re(r) < 0$, then

$$\frac{r}{\pi} \int_0^1 (1-t)^{-1-\frac{r}{\pi}} (t^{-\frac{r}{\pi}} - 1) dt = \frac{1}{2} \left(1 - \frac{\Gamma(1-2r)^2}{\Gamma(1-4r)} \right).$$

This implies that the radius of convergence of $\frac{r}{\pi} \int_0^1 (1-t)^{-1-\frac{r}{\pi}} (t^{-\frac{r}{\pi}} - 1) dt$ is $1/4$, so this series belongs to $\mathbb{R}_+ \{\{r\}\}_0$. Plugging this in Lemma 9.6, we get

$$\sum_{n \geq 0} |(\log \tilde{\Phi}_{KZ})_n|_{f_2} r^n \leq \log(2 - e^{\frac{1}{2} \left(1 - \frac{\Gamma(1-2r)^2}{\Gamma(1-4r)} \right)})^{-1},$$

where the series in the r.h.s. lies in $\mathbb{R}_+ \{\{r\}\}_0$ (being a composition of two series in $\mathbb{R}_+ \{\{r\}\}_0$).

Let us now prove that $(\log \tilde{\Phi}_{KZ})^\mathfrak{g} \in \mathfrak{g} \{\{\mathfrak{g}^2\}\}_0$ is an analytic germ. By Ado's theorem, there exists an injective morphism $\rho : \mathfrak{g} \rightarrow M_N(\mathbf{k})$, where $\mathbf{k} = \mathbb{R}$ or \mathbb{C} , hence an injective morphism $\tilde{\rho} : \mathfrak{g} \rightarrow M_N(\mathbb{C})$. Equip \mathfrak{g} with the norm $|x|_{\mathfrak{g}} := \|\tilde{\rho}(x)\|$. We recall that all the norms on \mathfrak{g} are equivalent, so it will suffice to prove analyticity w.r.t. $|\cdot|_{\mathfrak{g}}$.

The degree n part of the series $(\log \tilde{\Phi}_{KZ})^\mathfrak{g}$ is the specialization to \mathfrak{g} of $(\log \tilde{\Phi}_{KZ})_n$. Now if $\psi \in f_2[n]$ and $\psi^\mathfrak{g} : \mathfrak{g} \times \mathfrak{g} \rightarrow \mathfrak{g}$ is its specialization to \mathfrak{g} , we have $|\psi^\mathfrak{g}(x, y)|_{\mathfrak{g}} = \|\psi(\tilde{\rho}(x), \tilde{\rho}(y))\| \leq |\psi|_{f_2} \sup(\|\tilde{\rho}(x)\|, \|\tilde{\rho}(y)\|)^n = |\psi|_{f_2} \sup(|x|_{\mathfrak{g}}, |y|_{\mathfrak{g}})^n$, therefore $|\psi^\mathfrak{g}| \leq |\psi|_{f_2}$. We then have

$$\sum_{n \geq 0} |(\log \tilde{\Phi}_{KZ})_n^\mathfrak{g}| r^n \leq \sum_{n \geq 0} |(\log \tilde{\Phi}_{KZ})_n|_{f_2} r^n \leq \log(2 - e^{\frac{1}{2} \left(1 - \frac{\Gamma(1-2r)^2}{\Gamma(1-4r)} \right)})^{-1},$$

together with the fact that the series in the right has positive radius of convergence, this implies the analyticity of the series $(\log \tilde{\Phi}_{KZ})^\mathfrak{g}$. \square

Proposition 9.4, together with the local analyticity of the CBH series, implies that the specialization of $\mu_{\tilde{\Phi}_{KZ}}$ belongs to $\text{TAut}_2^{an}(\mathfrak{g})$. It follows that $A(x, y)$, $B(x, y)$ are analytic germs, and so

$$(KV2) (A^{\mathbb{R}}, B^{\mathbb{R}}) \text{ is an analytic germ } \mathfrak{g}^2 \rightarrow \mathfrak{g}^2.$$

All this implies that $(A^{\mathbb{R}}, B^{\mathbb{R}})$ is a solution of the 'original' KV conjecture (as formulated in [KV]) and proves 1) in Theorem 2.8.

Let us now prove Theorem 2.8, 2). One checks easily that if (A, B) is a solution of the 'original' KV conjecture, then $(A_s, B_s) := (A + s(\log(e^x e^y) - x), B + s(\log(e^x e^y) - y))$ is a family of solutions. In fact, if $\mu \in \text{SolKV}(\mathbf{k})$ and $[[A, B]] = -\kappa(\mu^{-1})$, then $[[A_s, B_s]] = -\kappa(\mu_s^{-1})$, where $\mu_s := \text{Inn}(e^{s(x+y)}) \circ \mu$; this corresponds to the action of 'trivial', degree 1 element of \mathfrak{ttv} on SolKV (see[AT]).

Finally, let us prove Theorem 2.8, 3). Let σ be the antilinear automorphism of \hat{f}_2 such that $\sigma(x) = -y$, $\sigma(y) = -x$. The series $\Phi_{KZ}(a, b)$ is real, therefore $\overline{\Phi_{KZ}(a, b)} = \tilde{\Phi}_{KZ}(-a, -b)$ (the bar denotes the complex conjugation). This implies that $\mu_{KZ} \circ \sigma = \text{Inn}(e^{-(x+y)/2}) \circ \sigma \circ \mu_{KZ}$. Using $\sigma \circ \ell \circ \sigma^{-1} = \ell$ and $\ell(x+y) = x+y$, we get

$$(\mu_{KZ} \circ \sigma \circ \mu_{KZ}^{-1}) \circ \ell \circ (\mu_{KZ} \circ \sigma \circ \mu_{KZ}^{-1})^{-1} = \ell + \text{inn}\left(\frac{1}{2}(x+y)\right),$$

where $\text{inn}(x+y)$ is the inner derivation $z \mapsto [x+y, z]$ of \hat{f}_2 . Using now $\mu_{KZ}^{-1}(x+y) = \log(e^x e^y)$, we get

$$(\sigma \circ \mu_{KZ}^{-1}) \circ \ell \circ (\sigma \circ \mu_{KZ}^{-1})^{-1} = \mu_{KZ}^{-1} \circ \ell \circ \mu_{KZ} + \text{inn}\left(\frac{1}{2} \log(e^x e^y)\right).$$

Since $\sigma \circ \ell \circ \sigma^{-1} = \ell$, $\mu^{-1} \circ \ell \circ \mu - \ell = -[A_{KZ}, B_{KZ}]$ and $\text{inn}(\frac{1}{2} \log(e^x e^y)) = [\frac{1}{2}(\log(e^x e^y) - x), \frac{1}{2}(\log(e^x e^y) - y)]$

$$\sigma \circ [A_{KZ}, B_{KZ}] \circ \sigma^{-1} = [A_{KZ}, B_{KZ}] - [\frac{1}{2}(\log(e^x e^y) - x), \frac{1}{2}(\log(e^x e^y) - y)].$$

This implies

$$(B_{KZ}(-y, -x), A_{KZ}(-y, -x)) = (A_{KZ}(x, y), B_{KZ}(x, y)) - (\frac{1}{2}(\log(e^x e^y) - x), \frac{1}{2}(\log(e^x e^y) - y)).$$

If now $(A', B') := (A_{KZ}, B_{KZ}) - \frac{1}{4}(\log(e^x e^y) - x, \log(e^x e^y) - y)$, this implies

$$(B'(-y, -x), A'(-y, -x)) = (A'(x, y), B'(x, y)),$$

which by taking real parts implies $(B_{-1/4}(-y, -x), A_{-1/4}(-y, -x)) = (A_{-1/4}(x, y), B_{-1/4}(x, y))$, proving Theorem 2.8, 3).

APPENDIX A. RESULTS ON CENTRALIZERS

A.1. The centralizer of t_{ij} in \mathfrak{t}_n .

Proposition A.1. *Let $i < j \in [n]$. If $x \in \mathfrak{t}_n$ is such that $[x, t_{ij}] = 0$, then there exists $\lambda \in \mathbf{k}$ and $y \in \mathfrak{t}_{n-1}$ such that $x = \lambda t_{ij} + y^{ij,1,2,\dots,i,\dots,j,\dots,n}$.*

Proof. We may and will assume that $i = 1, j = 2$. We then prove the result by induction on n . It is obvious when $n = 2$. Assume that it has been proved at step $n - 1$ and let us prove it at step n . We have $\mathfrak{t}_n = \mathfrak{t}_{n-1} \oplus \mathfrak{f}_{n-1}$, where \mathfrak{t}_{n-1} is the Lie subalgebra generated by the t_{ij} , $i \neq j \in \{1, \dots, n - 1\}$ and \mathfrak{f}_{n-1} is freely generated by the $t_{1n}, \dots, t_{n-1,n}$. Both \mathfrak{t}_{n-1} and \mathfrak{f}_{n-1} are Lie subalgebras of \mathfrak{t}_n , stable under the inner derivation $[t_{12}, -]$. Then if $x \in \mathfrak{t}_n$ is such that $[t_{12}, x] = 0$, we decompose $x = x' + f$, with $x' \in \mathfrak{t}_{n-1}$, $f \in \mathfrak{f}_{n-1}$, $[t_{12}, x'] = [t_{12}, f] = 0$. By the induction hypothesis, we have $x' = \lambda t_{12} + (y')^{12,3,\dots,n-1}$, where $y' \in \mathfrak{t}_{n-2}$ and $\lambda \in \mathbf{k}$.

Let us set $x_i = t_{in}$ for $i = 1, \dots, n - 1$. The derivation $[t_{12}, -]$ of \mathfrak{f}_{n-1} is given by $x_1 \mapsto [x_1, x_2]$, $x_2 \mapsto [x_2, x_1]$, $x_i \mapsto 0$ for $i > 2$. In terms of generators $y_1 = x_1, y_2 = x_1 + x_2, y_3 = x_3, \dots, y_{n-1} = x_{n-1}$, it is given by $y_1 \mapsto [y_1, y_2]$, $y_i \mapsto 0$ for $i > 1$.

Lemma A.2. *The kernel of the derivation $y_1 \mapsto [y_1, y_2]$, $y_i \mapsto 0$ for $i > 1$ of \mathfrak{f}_{n-1} coincides with the Lie subalgebra $\mathfrak{f}_{n-2} \subset \mathfrak{f}_{n-1}$ generated by y_2, \dots, y_{n-1} .*

Proof of Lemma. Let us prove that the kernel of the induced derivation of $U(\mathfrak{f}_{n-1})$ is $U(\mathfrak{f}_{n-2})$. We have a linear isomorphism $U(\mathfrak{f}_{n-1}) \simeq \oplus_{k \geq 1} U(\mathfrak{f}_{n-2})^{\otimes k}$, whose inverse takes $u_1 \otimes \dots \otimes u_k$ to $u_1 y_1 u_2 y_1 \dots y_1 u_k$. The derivation $[t_{12}, -]$ of $U(\mathfrak{f}_{n-1})$ is then transported to the direct sum of the endomorphisms of $U(\mathfrak{f}_{n-2})^{\otimes k}$

$$(24) \quad u \mapsto (y_2^{(2)} + \dots + y_2^{(k)})u - u(y_2^{(1)} + \dots + y_2^{(k-1)})$$

(this is 0 of $k = 1$; $y_2^{(i)} = 1^{\otimes i-1} \otimes y_2 \otimes 1^{\otimes k-i}$; we make use of the algebra structure of $U(\mathfrak{f}_{n-2})^{\otimes k}$). Each of these endomorphisms has degree 1 for the filtration of $U(\mathfrak{f}_{n-2})^{\otimes k}$ induced by the PBW filtration of $U(\mathfrak{f}_{n-2})$ (the part of degree $\leq d$ of $U(\mathfrak{f}_{n-2})$ for this filtration consists of combinations of products of $\leq d$ elements of \mathfrak{f}_{n-2}) and the associated graded endomorphism of $S(\mathfrak{f}_{n-2})^{\otimes k}$ is the multiplication by $y_2^{(k)} - y_2^{(1)}$, which is injective if $k \geq 1$, so (24) is injective for $k \geq 1$; the kernel of the direct sum of maps (24) therefore coincides with the degree 1 part $U(\mathfrak{f}_{n-2})$, which transports to $U(\mathfrak{f}_{n-2}) \subset U(\mathfrak{f}_{n-1})$. So the kernel of the derivation $[t_{12}, -]$ of $U(\mathfrak{f}_{n-1})$ is $U(\mathfrak{f}_{n-2})$. The kernel of the derivation $[t_{12}, -]$ of \mathfrak{f}_{n-1} is then $\mathfrak{f}_{n-1} \cap U(\mathfrak{f}_{n-2}) = \mathfrak{f}_{n-2}$. \square

End of proof of Proposition A.1. It follows that f expresses as $P(t_{1n} + t_{2n}, t_{3n}, \dots, t_{n-1,n})$. Then if we set $f' := P(t_{1,n-1}, \dots, t_{n-2,n-1})$, we get $f = (f')^{12,3,\dots,n}$ so $x = x' + f = \lambda t_{12} + ((y')^{1,2,\dots,n-1} + f')^{12,3,\dots,n}$, as wanted. \square

A.2. The centralizer of x_{ij} in PB_n .

Proposition A.3. *If $g \in \text{PB}_n(\mathbf{k})$ commutes with x_{12} , then there exists $\lambda \in \mathbf{k}$ and $h \in \text{PB}_{n-1}(\mathbf{k})$ such that $g = x_{12}^\lambda h^{\overline{12,3,\dots,n}}$.*

Since x_{ij} is conjugated to x_{12} , it is easy to derive from this the centralizer of x_{ij} in $\text{PB}_n(\mathbf{k})$.

Proof. Note that x_{12} commutes with the image of $\text{PB}_{n-1}(\mathbf{k}) \rightarrow \text{PB}_n(\mathbf{k})$, $h \mapsto h^{\overline{12,3,\dots,n}}$, so that $U_0 := \{x_{12}^\lambda h^{\overline{12,3,\dots,n}} \mid h \in \text{PB}_{n-1}(\mathbf{k}), \lambda \in \mathbf{k}\}$ is an algebraic subgroup of $\text{PB}_n(\mathbf{k})$. Let $U \subset \text{PB}_n(\mathbf{k})$ be the centralizer of x_{12} ; then $U_0 \subset U$, and we need to prove that $U_0 = U$.

We have $U_0 = \exp(u_0)$, $U = \exp(u)$, where $u_0 = \mathbf{k} \log x_{12} \oplus \text{Im}(\mathfrak{pb}_{n-1}^{\overline{12,3,\dots,n}} \rightarrow \mathfrak{pb}_n)$ and $u = \{x \in \mathfrak{pb}_n \mid [\log x_{12}, x] = 0\}$, where $\mathfrak{pb}_n := \text{Lie PB}_n(\mathbf{k})$. Then the lower central series defines a complete decreasing filtration of \mathfrak{pb}_n , with $F^1 \mathfrak{pb}_n = \mathfrak{pb}_n$ and $F^{i+1} \mathfrak{pb}_n = [\mathfrak{pb}_n, F^i \mathfrak{pb}_n]$. The associated graded Lie algebra is \mathfrak{t}_n , i.e., $\mathfrak{t}_n = \bigoplus_{i \geq 1} \mathfrak{t}_n[i] = \bigoplus_{i \geq 1} F^i \mathfrak{pb}_n / F^{i+1} \mathfrak{pb}_n$.

Set $F^i u := u \cap F^i \mathfrak{pb}_n$, $F^i u_0 := u_0 \cap F^i \mathfrak{pb}_n$. We will prove that the images of $F^i u_0$ and $F^i u$ in $\mathfrak{t}_n[i]$ coincide. Clearly, $\text{Im}(F^i u_0 \rightarrow \mathfrak{t}_n[i]) \subset \text{Im}(F^i u \rightarrow \mathfrak{t}_n[i])$.

Conversely, projecting the identity $[\log x_{12}, x] = 0$ modulo $F^{i+1} \mathfrak{pb}_n$, we get

$$(25) \quad \text{Im}(F^i u \rightarrow \mathfrak{t}_n[i]) \subset \{x \in \mathfrak{t}_n[i] \mid [t_{12}, x] = 0\},$$

and since $x \mapsto x^{\overline{12,\dots,n}}$ takes $F^i \mathfrak{pb}_{n-1}$ to $F^i \mathfrak{pb}_n$, we have $(F^i \mathfrak{pb}_{n-1})^{\overline{12,\dots,n}} \subset F^i u_0$ if $i > 1$ and $(F^1 \mathfrak{pb}_{n-1})^{\overline{12,\dots,n}} \oplus \mathbf{k} \log x_{12} \subset F^1 u_0$; projecting these inclusions, modulo $F^{i+1} \mathfrak{pb}_n$, we get

$$(26) \quad \text{Im}(F^i u_0 \rightarrow \mathfrak{t}_n[i]) \supset \mathfrak{t}_{n-1}[i]^{\overline{12,\dots,n}} \text{ if } i > 1 \text{ and } \text{Im}(F^1 u_0 \rightarrow \mathfrak{t}_n[1]) \supset \mathfrak{t}_{n-1}[1]^{\overline{12,\dots,n}} \oplus \mathbf{k} t_{12}.$$

Using (25), (26) and Proposition A.1, we get $\text{Im}(F^i u \rightarrow \mathfrak{t}_n[i]) \subset \text{Im}(F^i u_0 \rightarrow \mathfrak{t}_n[i])$. It follows that these spaces are equal, which implies (as both u_0 and u are closed for the topology of \mathfrak{pb}_n) that $u_0 = u$. So $U_0 = U$. \square

Remark A.4. One can also prove Proposition A.3 similarly to Proposition A.1, by induction on n and using the fact that the automorphism $\text{Ad}_{x_{12}}$ of the topologically free group generated by the x_{in} identifies with the automorphism $\exp(\text{ad } t_{12})$ of the topologically free Lie algebra generated by the t_{in} (using the identification $(x_{1n}, x_{1n}x_{2n}, x_{3n}, \dots, x_{n-1,n}) \leftrightarrow (e^{t_{1n}}, e^{t_{1n}+t_{2n}}, e^{t_{3n}}, \dots, e^{t_{n-1,n}})$).

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