

ON A GENERALIZED NOTION OF CUMULANTS

TAKAHIRO HASEBE AND HAYATO SAIGO

ABSTRACT. We propose a generalization of the notion of (joint) cumulants, associated to various notions of “independence” in the context of noncommutative probability. This note is mainly based on [6, 7].

[2000]Primary 46L53, 46L54; Secondary 05A18
 Cumulants, noncommutative probability

1. WHAT ARE CUMULANTS?

In the usual context of probability theory, the n -th cumulant $k_n(X)$ for a random variable X with all m -th moments $M_m(X) := E(X^m)$ is defined as follows:

$$\exp\left(\sum_{n=1}^{\infty} \frac{k_n(X)}{n!} t^n\right) = \sum_{m=0}^{\infty} \frac{M_m(X)}{m!} t^m$$

For example, $k_1(X) = E(X)$ is nothing but the usual expectation of X and $k_2(X) = V(X) := E((X - E(X))^2)$ is called the variance of X . We pick up three essential properties of $k_n(X)$:

- (k1) $k_n(\lambda X) = \lambda^n k_n(X)$
- (k2) There exists a polynomial P_n such that

$$k_n(X) = M_n(X) + P_n(\{M_p(X)\}_{1 \leq p \leq n-1}).$$

- (k3) For independent random variables X and Y , $k_n(X + Y) = k_n(X) + k_n(Y)$.

By making use of these properties, you can easily derive the central limit theorem or Poisson’s law of small numbers (at least for the random variables with all finite moments). It shows that cumulants and their properties above play essential role in probability theory.

Moreover, we can define the multivariate version of cumulants, so called “joint cumulants” (multivariate cumulants), which satisfy the following:

- (K1) Multilinearity: $K_n : \mathcal{A}^n \rightarrow \mathbb{C}$ is multilinear, where \mathcal{A} denotes an algebra of random variables (with all finite moments).

- (K2) Polynomiality: There exists a polynomial P_n such that

$$K_n(X_1, \dots, X_n) = E(X_1 \cdots X_n) + P_n(\{E(X_{i_1} \cdots X_{i_p})\}_{\substack{1 \leq p \leq n-1, \\ i_1 < \dots < i_p}}).$$

- (K3) Vanishment: If X_1, \dots, X_n are divided into two independent parts, i.e., there exist nonempty, disjoint subsets $I, J \subset \{1, \dots, n\}$ such that $I \cup J = \{1, \dots, n\}$ and $\{X_i, i \in I\}, \{X_i, i \in J\}$ are independent, then

$$K_n(X_1, \dots, X_n) = 0.$$

T.H. is supported by Grant-in-Aid for JSPS Fellows.

Covariance $C(X, Y) := E((X - E(X))(Y - E(Y)))$ is an example of joint cumulants ($n = 2$ case). As is well known, covariance is useful to evaluate the degree of interdependence between random variables (e.g., $C(X, Y) = 0$ if X and Y are independent). In general, we have quantitative evaluation of “independence” by making use of joint cumulants.

In this paper, we propose a generalization of (joint) cumulants associated to “various kinds of independence” in the context of noncommutative probability, which is discussed in the next section.

2. NONCOMMUTATIVE PROBABILITY

In noncommutative probability theory, we have many kinds of generalized notion of “independence”. The essential idea is that a notion of “independence” provides canonical factorization rules for (joint) moments such as $\varphi(X_1 \dots X_n)$.

Let (\mathcal{A}, φ) be an algebraic probability space, i.e., a pair of a unital $*$ -algebra and a state on it. Let \mathcal{A}_λ be $*$ -subalgebras, where $\lambda \in \Lambda$ are indices. The above mentioned four independences are defined as rules to calculate moments $\varphi(X_1 \dots X_n)$ for

$$X_i \in \mathcal{A}_{\lambda_i}, \lambda_i \neq \lambda_{i+1}, 1 \leq i \leq n-1, n \geq 2.$$

Definition 2.1. (1) Tensor independence: $\{\mathcal{A}_\lambda\}$ is tensor independent if

$$\varphi(X_1 \dots X_n) = \prod_{\lambda \in \Lambda} \varphi\left(\overrightarrow{\prod_{i: X_i \in \mathcal{A}_\lambda} X_i}\right),$$

where $\overrightarrow{\prod_{i \in V} X_i}$ is the product of X_i , $i \in V$ in the same order as they appear in $X_1 \dots X_n$.

(2) Free independence [19]: We assume all \mathcal{A}_λ contain the unit of \mathcal{A} . $\{\mathcal{A}_\lambda\}$ is free independent if

$$\varphi(X_1 \dots X_n) = 0$$

holds whenever $\varphi(X_1) = \dots = \varphi(X_n) = 0$.

(3) Boolean independence [18]: $\{\mathcal{A}_\lambda\}$ is Boolean independent if

$$\varphi(X_1 \dots X_n) = \varphi(X_1) \dots \varphi(X_n).$$

(4) Monotone independence [10]: We assume that Λ is equipped with a linear order $<$. Then $\{\mathcal{A}_\lambda\}$ is monotone independent if

$$\varphi(X_1 \dots X_i \dots X_n) = \varphi(X_i) \varphi(X_1 \dots X_{i-1} X_{i+1} \dots X_n)$$

holds when i satisfies $\lambda_{i-1} < \lambda_i$ and $\lambda_i > \lambda_{i+1}$ (one of the inequalities is eliminated when $i = 1$ or $i = n$).

Many probabilistic notions have been introduced for each kind of independence. Analogy of cumulants is a central topic in this field ([19, 20, 16] for free case, [18, 8] for Boolean case).

Lehner [8] unified many kinds of cumulants in noncommutative probability theory in terms of Good’s formula. A crucial idea was a very general notion of independence called an exchangeability system. Monotone cumulants however cannot be defined in Lehner’s approach. This is because monotone independence is noncommutative: if X and Y are monotone independent, then Y and X are not necessarily monotone independent. Therefore, the concept of “mutual independence of random

variables" fails to hold. In spite of this, we found a way to define monotone cumulants uniquely for single variable in [6]. In the present paper, we generalize the method to define joint cumulants for monotone independence.

For tensor, free and Boolean cumulants, the following properties are considered to be basic, as we have discussed for classical case (a special case for tensor case) in introduction.

- (K1) Multilinearity: $K_n : \mathcal{A}^n \rightarrow \mathbb{C}$ is multilinear.
 (K2) Polynomiality: There exists a polynomial P_n such that

$$K_n(X_1, \dots, X_n) = \varphi(X_1 \cdots X_n) + P_n(\{\varphi(X_{i_1} \cdots X_{i_p})\}_{\substack{1 \leq p \leq n-1, \\ i_1 < \cdots < i_p}}).$$

- (K3) Vanishment: If X_1, \dots, X_n are divided into two independent parts, i.e., there exist nonempty, disjoint subsets $I, J \subset \{1, \dots, n\}$ such that $I \cup J = \{1, \dots, n\}$ and $\{X_i, i \in I\}, \{X_i, i \in J\}$ are independent, then $K_n(X_1, \dots, X_n) = 0$.

Cumulants for single variable can be defined from joint cumulants: $K_n(X) := K_n(X, \dots, X)$. Clearly the additivity of cumulants for single variable follows from the property (K3): $K_n(X + Y) = K_n(X) + K_n(Y)$ if X and Y are independent.

The additivity of monotone cumulants for single variable does not hold because of the noncommutativity of monotone independence. Instead, we proved in [6] that monotone cumulants for single variable satisfy that $K_n^M(N.X_1) := K_n^M(X_1 + \cdots + X_N) = NK_n^M(X_1)$ holds if $X_1 \cdots, X_N$ are identically distributed and monotone independent.

The notion of a "dot operation" such as $N.X_1$ is important throughout this paper. This notion was used in the classical umbral calculus [14]. The next section is devoted to the definition of the dot operation associated to each notion of independence.

It enables us to define joint cumulants for natural independence in a unified way, in the section 4, along an idea similar to [6]. The new notion here is monotone joint cumulants denoted as K_n^M . The property (K3) however does not hold for the reason above. Alternatively, it is expected that (K3) holds for identically distributed random variables in view of the single-variable case. This is, however, not the case; as we shall see later, $K_3^M(X, Y, X) \neq 0$ for monotone independent, identically distributed X and Y . To solve this problem, we generalize the condition (K3) in Section 4. We can prove the uniqueness of joint cumulants under the generalized condition. Moreover, we prove the moment-cumulant formulae for the monotone case in Section 5.

3. DOT OPERATION

We used in [6] the dot operation associated to a given notion of independence. This is also crucial in the definition of joint cumulants for natural independence, that is, tensor, free, Boolean and monotone ones.

Definition 3.1. We fix a notion of independence among tensor, free, Boolean and monotone. Let (\mathcal{A}, φ) be an algebraic probability space. We take copies $\{X^{(j)}\}_{j \geq 1}$ (in some extended algebraic probability space) for every $X \in \mathcal{A}$ such that

- (1) $\varphi(X_1^{(j)} X_2^{(j)} \cdots X_n^{(j)}) = \varphi(X_1 X_2 \cdots X_n)$ for any $X_i \in \mathcal{A}$, $j, n \geq 1$;
- (2) the subalgebras $\mathcal{A}^{(j)} := \{X^{(j)}\}_{X \in \mathcal{A}}$, $j \geq 1$ are independent.

Then we define the dot operation $N.X$ by

$$N.X = X^{(1)} + \dots + X^{(N)}$$

for $X \in \mathcal{A}$ and a natural number $N \geq 0$. We understand that $0.X = 0$. Similarly we can iterate the dot operation more than once; for instance $N.(M.X)$ can be defined (in a suitable space. For details, see [7]).

Remark 3.2. The notation $N.X$ is inspired from “the classical umbral calculus” [14]. Indeed, this notion can be used to develop some kind of umbral calculus in the context of quantum probability.

The power of “dot operation methods” is based on the next proposition;

Proposition 3.3. (*Associativity of dot operation*). *We fix a notion of independence among the four. Then the dot operation satisfies that*

$$\varphi(N.(M.X_1) \cdots N.(M.X_n)) = \varphi((MN).X_1 \cdots (MN).X_n)$$

for any $X_i \in \mathcal{A}$, $n \geq 1$.

Proof. $N.(M.X_i)$ is the sum

$$(3.1) \quad X_i^{(1,1)} + X_i^{(2,1)} + \dots + X_i^{(M,1)} + X_i^{(1,2)} + \dots + X_i^{(M,N)},$$

where $\{X_i^{(1,j)}\}_{i=1}^n, \dots, \{X_i^{(M,j)}\}_{i=1}^n$ are independent for each j and $\{X_i^{(1,j)} + X_i^{(2,j)} + \dots + X_i^{(M,j)}\}_{i=1}^n$ ($j = 1, \dots, N$) are independent. On the other hand, $(NM).X_i$ is the sum

$$(3.2) \quad X_i^{(1)} + \dots + X_i^{(NM)},$$

where $\{X_i^{(1)}\}_{i=1}^n, \dots, \{X_i^{(NM)}\}_{i=1}^n$ are independent. Since natural independence is associative, the random variables in (3.2) satisfy a stronger condition of independence than those in (3.1). By the way, the condition of independence in (3.1) is enough to calculate the expectation only by sums and products of joint moments of X_1, \dots, X_n . Therefore, $\varphi(N.(M.X_1) \cdots N.(M.X_n))$ must be equal to $\varphi((MN).X_1 \cdots (MN).X_n)$. \square

4. GENERALIZED CUMULANTS

The following properties are basic for joint cumulants in tensor, free and Boolean independences.

(K1) Multilinearity: $K_n : \mathcal{A}^n \rightarrow \mathbb{C}$ is multilinear.

(K2) Polynomiality: There exists a polynomial P_n such that

$$K_n(X_1, \dots, X_n) = \varphi(X_1 \cdots X_n) + P_n(\{\varphi(X_{i_1} \cdots X_{i_p})\}_{\substack{1 \leq p \leq n-1, \\ i_1 < \dots < i_p}}).$$

(K3) Vanishment: If X_1, \dots, X_n are divided into two independent parts, i.e., there exist nonempty, disjoint subsets $I, J \subset \{1, \dots, n\}$ such that $I \cup J = \{1, \dots, n\}$ and $\{X_i, i \in I\}, \{X_i, i \in J\}$ are independent, then $K_n(X_1, \dots, X_n) = 0$.

Monotone cumulants do not satisfy (K3), even if X_i ’s are identically distributed. For instance, $K_3^M(X, Y, X) = \frac{1}{2}(\varphi(X^2)\varphi(Y) - \varphi(X)\varphi(Y)\varphi(X))$ if X and Y are monotone independent (see Example 5.4 in Section 5). Instead we consider the following property.

(K3’) Extensivity: $K_n(N.X_1, \dots, N.X_n) = NK_n(X_1, \dots, X_n)$.

The terminology of extensivity is taken from the property of Boltzmann entropy.

Remark 4.1. More generally, the following condition is enough to prove the uniqueness of cumulants.

(K3'') There exists a polynomial Q_n without a constant or a linear term with respect to N such that

$$K_n(N.X_1, \dots, N.X_n) = NK_n(X_1, \dots, X_n) + Q_n(N, \{\varphi(X_{i_1} \cdots X_{i_p})\}_{\substack{1 \leq p \leq n-1, \\ i_1 < \cdots < i_p}}).$$

There is no change in the proof and we do not consider this condition anymore in this paper.

In the tensor, free and Boolean cases, it is well known that there exist cumulants which satisfy (K1), (K2) and (K3), and hence generalized cumulants exist obviously.

Here we discuss the uniqueness of generalized cumulants for all natural independences, including monotone independence.

Theorem 4.2. *For any one of tensor, free, Boolean and monotone independences, joint cumulants satisfying (K1), (K2) and (K3') are unique.*

Proof. We fix a notion of independence. Let $K_n^{(1)}$ and $K_n^{(2)}$ be two cumulants with possibly different polynomials in the condition (K2). Then $\varphi(N.X_1 \cdots N.X_n)$ is of such a form as

$$\begin{aligned} (4.1) \quad \varphi(N.X_1 \cdots N.X_n) &= NK_n^{(1)}(X_1, \dots, X_n) + \\ &\quad N^2 \cdot (\text{a polynomial of } N \text{ and } \{K_p^{(1)}(X_{i_1} \cdots X_{i_p})\}_{\substack{1 \leq p \leq n-1, \\ i_1 < \cdots < i_p}}) \\ &= NK_n^{(2)}(X_1, \dots, X_n) + \\ &\quad N^2 \cdot (\text{a polynomial of } N \text{ and } \{K_p^{(2)}(X_{i_1} \cdots X_{i_p})\}_{\substack{1 \leq p \leq n-1, \\ i_1 < \cdots < i_p}}). \end{aligned}$$

The coefficients of N in the above two lines must be the same. Therefore, $K_n^{(1)} = K_n^{(2)}$. □

The above theorem implies that generalized cumulants coincide with the usual cumulants in tensor, free and Boolean independences since (K3') is weaker than (K3). This is nothing but a new characterization of those cumulants.

The existence of cumulants is not trivial. A key fact is the following.

Proposition 4.3. *For tensor, free, Boolean and monotone independence, $\varphi(N.X_1 \cdots N.X_n)$ is a polynomial of N and $\varphi(X_{i_1} \cdots X_{i_k})$ ($1 \leq k \leq n, i_1 < \cdots < i_k$) without a constant term with respect to N .*

Proof. First we notice that there exists a polynomial S_n (depending on the choice of independence) for any $n \geq 1$ such that if $\{X_i\}_{i=1}^n$ and $\{Y_j\}_{j=1}^n$ are independent,

$$\begin{aligned} (4.2) \quad \varphi((X_1 + Y_1) \cdots (X_n + Y_n)) &= \varphi(X_1 \cdots X_n) + \varphi(Y_1 \cdots Y_n) \\ &\quad + S_n(\{\varphi(X_{i_1} \cdots X_{i_p})\}_{\substack{1 \leq p \leq n-1, \\ i_1 < \cdots < i_p}}, \{\varphi(Y_{j_1} \cdots Y_{j_q})\}_{\substack{1 \leq q \leq n-1, \\ j_1 < \cdots < j_q}}). \end{aligned}$$

Let $\{X_i^{(j)}\}_{1 \leq i \leq n, j \geq 1}$ be copies of X_1, \dots, X_n appearing in Definition 3.1. We prove the theorem by induction about n . The claim is obvious for $n = 1$ since the

expectation is linear. We assume that the claim is the case for $n \leq k$. We replace X_i and Y_i in (4.2) by $X_i^{(1)}$ and $X_i^{(2)} + \dots + X_i^{(L+1)}$, respectively. Then one has

$$\begin{aligned} & \varphi((L+1).X_1 \cdots (L+1).X_{k+1}) - \varphi(L.X_1 \cdots L.X_{k+1}) \\ &= \varphi(X_1 \cdots X_{k+1}) + S_{k+1}(\{\varphi(X_{i_1} \cdots X_{i_p})\}_{\substack{1 \leq p \leq k, \\ i_1 < \dots < i_p}}, \{\varphi(L.X_{j_1} \cdots L.X_{j_q})\}_{\substack{1 \leq q \leq k, \\ j_1 < \dots < j_q}}), \end{aligned}$$

where $1 \leq p, q \leq k$, $i_1 < \dots < i_p$ and $j_1 < \dots < j_q$. The right hand side is a polynomial of L by assumption. Therefore, the sum

$$N\varphi(X_1 \cdots X_{k+1}) + \sum_{L=0}^{N-1} S_{k+1}(\{\varphi(X_{i_1} \cdots X_{i_p})\}_{\substack{1 \leq p \leq k, \\ i_1 < \dots < i_p}}, \{\varphi(L.X_{j_1} \cdots L.X_{j_q})\}_{\substack{1 \leq q \leq k, \\ j_1 < \dots < j_q}})$$

is also a polynomial of N without a constant. \square

Definition 4.4. We define the n -th monotone (resp. tensor, free, Boolean) cumulant K_n^M (resp. K_n^T, K_n^F, K_n^B) by the coefficient of N in $\varphi(N.X_1 \cdots N.X_n)$ for monotone (resp. tensor, free, Boolean) independence.

It is easy to see that multilinearity (K1) and polynomiality (K2) holds. Extensivity (K3') comes from the associative law of the dot operation, as follows.

Proposition 4.5. *The cumulants $K_n^M, K_n^T, K_n^F, K_n^B$ satisfy the condition (K3').*

Proof. The idea is the same as in [6]. We recall that the dot operation is associative:

$$\varphi(M.(N.X_1) \cdots M.(N.X_n)) = \varphi((MN).X_1 \cdots (MN).X_n).$$

By definition, $\varphi(M.(N.X_1) \cdots M.(N.X_n))$ is of such a form as

$$K_n(N.X_1, \dots, N.X_n) + M^2 \cdot (\text{a polynomial of } M \text{ and } \{\varphi(N.X_{i_1} \cdots N.X_{i_p})\}_{\substack{1 \leq p \leq n-1, \\ i_1 < \dots < i_p}}).$$

Also by definition $\varphi((MN).X_1 \cdots (MN).X_n)$ is of such a form as

$$MNK_n(X_1, \dots, X_n) + M^2N^2 \cdot (\text{a polynomial of } MN \text{ and } \{\varphi(X_{i_1} \cdots X_{i_p})\}_{\substack{1 \leq p \leq n-1, \\ i_1 < \dots < i_p}}).$$

The coefficients of M coincide, and hence, (K3') holds. \square

Remark 4.6. We know that K^T, K^F and K^B are no other than the usual tensor, free and Boolean cumulants, respectively, because of Theorem 4.2. Therefore, it is obvious that the property (K3) holds. However, we can also prove (K3) directly on the basis of Definition 4.4. See [7].

Corollary 4.7. *For any one of tensor, free and Boolean independences, cumulants satisfying (K1), (K2) and (K3) uniquely exist.*

5. THE MONOTONE MOMENT-CUMULANT FORMULA

We call a subset $V \subset \underline{n}$ a block of interval type if there exist i, j , $1 \leq i \leq n, 0 \leq j \leq n - i$ such that $V = \{i, \dots, i + j\}$. We denote by $IB(n)$ the set of all blocks of interval type. The empty block is assumed not to be contained in $IB(n)$. Let V be a subset of $\{1, \dots, n\}$. We express V as $V = \{k_1, \dots, k_m\}$ with $k_1 < \dots < k_m$, $m = |V|$. We collect all $1 \leq i \leq m + 1$ satisfying $k_{i-1} + 1 < k_i$, where $k_0 := 0$ and $k_{m+1} := n + 1$. We label them i_1, \dots, i_p . Let V_1, \dots, V_p be blocks defined by $V_q := \{k_{i_q-1} + 1, \dots, k_{i_q} - 1\}$.

In the above notation, we can prove the following.

Proposition 5.1. *If $\{X_i\}_{i=1}^n$ and $\{Y_j\}_{j=1}^p$ are monotone independent,*

$$(5.1) \quad \varphi((X_1 + Y_1) \cdots (X_n + Y_n)) = \sum_{V \subset \underline{n}} \varphi(X_V) \prod_{j=1}^p \varphi(Y_{V_j}).$$

Proof. The subsets V_j play roles of choosing positions of Y_i 's. Then the claim follows immediately. \square

Since $\varphi(N.X_1 \cdots N.X_n)$ is a polynomial of N , we can define $\varphi(t.X_1 \cdots t.X_n)$ for $t \in \mathbb{R}$. We denote this by $\varphi_t(X_1, \dots, X_n)$.

Corollary 5.2. *We have the following recurrent differential equations.*

$$(1) \quad \frac{d}{dt} \varphi_t(X_1, \dots, X_n) = \sum_{V \subset \underline{n}, V \neq \emptyset} K_{|V|}^M(X_V) \prod_{j=1}^p \varphi_t(X_{V_j}).$$

$$(2) \quad \frac{d}{dt} \varphi_t(X_1, \dots, X_n) = \sum_{V \in IB(n)} K_{|V|}^M(X_V) \varphi_t(X_{V^c}).$$

Proof. We replace X_i and Y_i in Proposition 5.1 by $N.X_i$ and $(N + M).X_i - N.X_i$ respectively. We notice that $\{N.X_i\}_{i=1}^n$ and $\{(N + M).X_i - N.X_i\}_{i=1}^n$ are monotone independent and that $(N + M).X_i - N.X_i$ is identically distributed to $M.X_i$. We replace N by t and M by s and then the equality

$$\varphi((t + s).X_1 \cdots (t + s).X_n) = \sum_{V \subset \underline{n}} \varphi(t.X_V) \prod_{j=1}^p \varphi(s.Y_{V_j})$$

holds, where $t.X_E$ means $t.X_{e_1} \cdots t.X_{e_r}$ for a subset $E = \{e_1, \dots, e_r\}$, $e_1 < \dots < e_r$. The equation (1) follows from the coefficient of t . The coefficient of s appears only when $V^c \in IB(n)$ and therefore we obtain (2) by replacing V^c by V . \square

Now we prove the moment-cumulant formula which generalizes the result in [6] for the single-variable case. Let $\mathcal{LP}(n)$ be the set of ordered partitions. An element of $\mathcal{LP}(n)$ is denoted as (π, λ) consisting of $\pi \in \mathcal{P}(n)$ and a linear order of the blocks of π . There are $|\pi|!$ ways to choose λ for each π . We denote by $V >_\lambda W$ if V is larger than W under an order λ .

We introduce a partial order $V \succ W$ for $V, W \in \mathcal{NC}(n)$ if there are $i, j \in W$ such that $i < k < j$ for all $k \in V$. Visually $V \succ W$ means that V lies in the inner side of W . We define a subset $\mathcal{M}(n)$ of $\mathcal{LP}(n)$ by

$$(5.2) \quad \mathcal{M}(n) := \{(\pi, \lambda); \pi \in \mathcal{NC}(n), \text{ if } V, W \in \pi \text{ satisfy } V \succ W, \text{ then } V >_\lambda W\}.$$

An element of $\mathcal{M}(n)$ is called a monotone partition. The set of monotone partitions was first introduced by Muraki in [11] and later independently found by Lenczewski and Salapata in [9].

Theorem 5.3. *The moment-cumulant formula is expressed as*

$$\varphi(X_1 \cdots X_n) = \sum_{(\pi, \lambda) \in \mathcal{M}(n)} \frac{1}{|\pi|!} K_\pi^M(X_1, \dots, X_n)$$

Proof. We prove this by induction about n . Assume that

$$\varphi_t(X_1 \cdots X_k) = \sum_{(\pi, \lambda) \in \mathcal{M}(k)} \frac{t^{|\pi|}}{|\pi|!} K_\pi^M(X_1, \dots, X_k).$$

holds for $t \in \mathbb{R}$ and $k \leq n$. We notice that an element in $\mathcal{M}(n)$ can be expressed as $(\pi, \lambda) = (V_1, \dots, V_{|\pi|})$ with $V_1 < \dots < V_{|\pi|}$. We can use a discussion similar to [5, 6]. (The prototype of the discussion is in [15].) Let $IB(k, m)$ be the subset of

$IB(k)$ defined by $\{V \in IB(k); |V| = m\}$. Let 1_k be the partition $\in \mathcal{P}(k)$ consisting of one block. There is a bijection $f : \mathcal{M}(n+1) \rightarrow \left(\bigcup_{k=1}^n \mathcal{M}(n+1-k) \times IB(n+1, k) \right) \cup \{1_{n+1}\}$ defined by

$$f : (V_1, \dots, V_{|\pi|}) \mapsto ((V_1, \dots, V_{|\pi|-1}), V_{|\pi|}).$$

Therefore, the sum $\sum_{(\pi, \lambda) \in \mathcal{M}(n)}$ can be replaced by $\sum_{V \in IB(n+1)} \sum_{(\sigma, \mu) \in \mathcal{M}(n+1-|V|)}$ and we have

$$\begin{aligned} \sum_{(\pi, \lambda) \in \mathcal{M}(n+1)} \frac{t^{|\pi|}}{|\pi|!} K_{\pi}^M(X_1, \dots, X_n) &= \sum_{V \in IB(n+1)} \sum_{(\sigma, \mu) \in \mathcal{M}(n+1-|V|)} \frac{t^{|\sigma|+1}}{(|\sigma|+1)!} K_{\sigma}^M(X_{V^c}) K_{|\mu|}^M(X_V) \\ &= \sum_{V \in IB(n+1)} \int_0^t ds \sum_{(\sigma, \mu) \in \mathcal{M}(n+1-|V|)} \frac{s^{|\sigma|}}{|\sigma|!} K_{\sigma}^M(X_{V^c}) K_{|\mu|}^M(X_V) \\ &= \sum_{V \in IB(n+1)} \int_0^t ds \varphi_s(X_{V^c}) K_{|\mu|}^M(X_V) \\ &= \int_0^t \frac{d}{ds} \varphi_s(X_1 \cdots X_{n+1}) ds \\ &= \varphi_t(X_1 \cdots X_{n+1}). \end{aligned}$$

We used assumption of induction in the third line and Corollary 5.2 (2) in the fourth line. The claim follows from the case $t = 1$. \square

Example 5.4. We show the monotone cumulants until the fourth order.

$$\begin{aligned} K_1^M(X_1) &= \varphi(X_1), \quad K_2^M(X_1, X_2) = \varphi(X_1 X_2) - \varphi(X_1)\varphi(X_2), \\ K_3^M(X_1, X_2, X_3) &= \varphi(X_1 X_2 X_3) - \varphi(X_1 X_2)\varphi(X_3) - \varphi(X_1)\varphi(X_2 X_3) - \frac{1}{2}\varphi(X_1 X_3)\varphi(X_2) \\ &\quad + \frac{3}{2}\varphi(X_1)\varphi(X_2)\varphi(X_3), \\ K_4^M(X_1, X_2, X_3, X_4) &= \varphi(X_1 X_2 X_3 X_4) - \varphi(X_1 X_2 X_3)\varphi(X_4) - \frac{1}{2}\varphi(X_1 X_3 X_4)\varphi(X_2) \\ &\quad - \frac{1}{2}\varphi(X_1 X_2 X_4)\varphi(X_3) - \varphi(X_1)\varphi(X_2 X_3 X_4) - \varphi(X_1 X_2)\varphi(X_3 X_4) \\ &\quad - \frac{1}{2}\varphi(X_1 X_4)\varphi(X_2 X_3) + \frac{3}{2}\varphi(X_1 X_2)\varphi(X_3)\varphi(X_4) + \frac{2}{3}\varphi(X_1 X_4)\varphi(X_2)\varphi(X_3) \\ &\quad + \frac{3}{2}\varphi(X_1)\varphi(X_2)\varphi(X_3 X_4) + \frac{1}{2}\varphi(X_1)\varphi(X_2 X_4)\varphi(X_3) + \frac{3}{2}\varphi(X_1)\varphi(X_2 X_3)\varphi(X_4) \\ &\quad + \frac{1}{2}\varphi(X_1 X_3)\varphi(X_2)\varphi(X_4) - \frac{8}{3}\varphi(X_1)\varphi(X_2)\varphi(X_3)\varphi(X_4). \end{aligned}$$

ACKNOWLEDGEMENTS

The authors thank Professor Izumi Ojima, Mr. Ryo Harada, Mr. Hiroshi Ando, Mr. Kazuya Okamura for discussions on the notion of independence. T.H. is supported by JSPS (KAKENHI 21-5106).

REFERENCES

- [1] S. Belinschi, Complex analysis methods in noncommutative probability, PhD thesis, Indiana University, 2005. Available in arXiv:math/0602343v1.
- [2] C. C. Cowen, Iteration and the solution of functional equations for functions analytic in the unit disk, *Trans. Amer. Math. Soc.* **265**, No. 1 (1981), 69–95.
- [3] A. Ben Ghorbal and M. Schürmann, Non-commutative notions of stochastic independence, *Math. Proc. Comb. Phil. Soc.* **133** (2002), 531–561.
- [4] T. Hasebe, Monotone convolution and monotone infinite divisibility from complex analytic viewpoint, *Infin. Dim. Anal. Quantum Probab. Relat. Top.* **13**, No. 1 (2010), 111–131.
- [5] T. Hasebe, Conditionally monotone independence I: Independence, additive convolutions and related convolutions, arXiv:0907.5473v3.
- [6] T. Hasebe and H. Saigo, The monotone cumulants, to appear in *Ann. Inst. Henri Poincaré Probab. Stat.* arXiv:0907.4896v3.
- [7] T. Hasebe and H. Saigo, Joint cumulants for natural independence. arXiv:1005.3900v2.
- [8] F. Lehner, Cumulants in noncommutative probability theory I, *Math. Z.* **248** (2004), 67–100.
- [9] R. Lenczewski and R. Sałapata, Discrete interpolation between monotone probability and free probability, *Infin. Dim. Anal. Quantum Probab. Rel. Topics*, **9**, No. 1 (2006), 77–106.
- [10] N. Muraki, Monotonic convolution and monotonic Lévy-Hinčin formula, preprint, 2000.
- [11] N. Muraki, The five independences as quasi-universal products, *Infin. Dim. Anal. Quantum Probab. Relat. Top.* **5**, No. 1 (2002), 113–134.
- [12] N. Muraki, The five independences as natural products, *Infin. Dim. Anal. Quantum Probab. Relat. Top.* **6**, No. 3 (2003), 337–371.
- [13] A. Nica and R. Speicher, *Lectures on the Combinatorics of Free Probability*, London Math. Soc. Lecture Note Series, vol. 335, Cambridge Univ. Press, 2006.
- [14] G.-C. Rota, B. D. Taylor, The classical umbral calculus, *SIAM J. Math. Anal.* **25** (1994), 694–711.
- [15] H. Saigo, A simple proof for monotone CLT, *Infin. Dim. Anal. Quantum Probab. Relat. Top.* **13**, No. 2 (2010), 339–343.
- [16] R. Speicher, Multiplicative functions on the lattice of non-crossing partitions and free convolution, *Math. Ann.* **298** (1994), 611–628.
- [17] R. Speicher, On universal products, in *Free Probability Theory*, ed. D. Voiculescu, Fields Inst. Commun., vol. 12 (Amer. Math. Soc., 1997), 257–266.
- [18] R. Speicher and R. Woroudi, Boolean convolution, in *Free Probability Theory*, ed. D. Voiculescu, Fields Inst. Commun., vol. 12 (Amer. Math. Soc., 1997), 267–280.
- [19] D. Voiculescu, Symmetries of some reduced free product algebras, *Operator algebras and their connections with topology and ergodic theory*, *Lect. Notes in Math.* **1132**, Springer (1985), 556–588.
- [20] D. Voiculescu, Addition of certain non-commutative random variables, *J. Funct. Anal.* **66** (1986), 323–346.
- [21] D. Voiculescu, K. J. Dykema and A. Nica, *Free Random Variables*, CRM Monograph Series, AMS, 1992.

GRADUATE SCHOOL OF SCIENCE, KYOTO UNIVERSITY, KYOTO 606-8502, JAPAN
E-mail address: hsb@kurims.kyoto-u.ac.jp

NAGAHAMA INSTITUTE OF BIO-SCIENCE AND TECHNOLOGY, SHIGA 606-8502, JAPAN
E-mail address: h_saigo@nagahama-i-bio.ac.jp