

A Chinese restaurant process for multiset permutations

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Abstract Multisets are like sets, except that they can contain multiple copies of their elements. If there are n_i copies of i , $1 \leq i \leq t$, in multiset M_t , then there are $\binom{n_1 + \dots + n_t}{n_1, \dots, n_t}$ possible permutations of M_t . Knuth showed how to factor any multiset permutation into cycles. For fixed n_i , $i \geq 1$, we show how to adapt the Chinese restaurant process, which generates random permutations on n elements with weighting $\theta^{\#\text{cycles}}$, $\theta > 0$, sequentially for $n = 1, 2, \dots$, to the multiset case, where we fix the n_i and build permutations on M_t sequentially for $t = 1, 2, \dots$. The number of cycles of a multiset permutation chosen uniformly at random, i.e. $\theta = 1$, has distribution given by the sum of independent negative hypergeometric distributed random variables. For all $\theta > 0$, and under the assumption that $n_i = O(1)$, we show a central limit theorem as $t \rightarrow \infty$ for the number of cycles.

Keywords Chinese restaurant process, random permutations, multiset

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1 Introduction

A growth rule which received considerable attention in the literature is the following preferential attachment algorithm on permutations written as the product of cycles known as the Chinese restaurant process (CRP) [1, 5, 9, 12–14, 16, 20, 23]. For $n \geq 1$, given a permutation of $[n-1] := \{1, 2, \dots, n-1\}$ which has been constructed at step $n-1$, element n is either appended to the permutation as a new singleton cycle with probability $\frac{\theta}{\theta+n-1}$, or inserted into a random position within the existing permutation with probability equal to $\frac{n-1}{\theta+n-1}$. Let S_n be the set of permutations on $[n]$. The permutation obtained at step n has the Ewens distribution, which is the uniform distribution on $n!$ permutations in the case $\theta = 1$, and, in general, has probability

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distribution $\theta^{|\pi|}/\theta_{(n)}$, $\pi \in S_n$, where $\theta_{(n)} := \theta(\theta + 1) \cdots (\theta + n - 1)$ and $|\pi|$ is the number of cycles in π .

Let Π_n be the random permutation of $[n]$ at the n th step of the CRP. The distribution of Π_n is invariant under relabelling. For different orders the permutations are consistent, in the sense that Π_m , for $m < n$, can be derived from Π_n by removing elements $m + 1, \dots, n$ from their cycles and deleting empty cycles if necessary.

The CRP expresses every permutation π of $[n]$ uniquely as the product

$$\pi = (x_{1,1} \dots x_{1,m_1} y_1)(x_{2,1} \dots x_{2,m_2} y_2) \cdots (x_{\tau,1} \dots x_{\tau,m_\tau} y_\tau), \quad \tau \geq 1,$$

where the following two conditions are satisfied:

1. $y_1 < y_2 < \cdots < y_\tau$
2. $y_i < x_{ij}$ for $1 \leq j \leq m_i, 1 \leq i \leq \tau$.

We will see in Section 2 that there is a similar unique expression for permutations of multisets.

The number of cycles in Π_n , denoted by K_n , has probability generating function (p.g.f.)

$$\mathbb{E}_z^{K_n} = \frac{(\theta z)_n}{(\theta)_n},$$

which corresponds to the distribution of the sum of n independent Bernoulli variables $K_n = \sum_{i=1}^n I_i$, $I_i \sim \text{Bernoulli}(\theta/(i + \theta - 1))$; see [1]. We have $I_i = 1$ exactly when the element i starts a new cycle. As $n \rightarrow \infty$,

$$K_n \sim \theta \log n \text{ a.s.}, \quad \frac{K_n - \theta \log n}{\sqrt{\theta \log n}} \xrightarrow{d} N(0, 1),$$

where \xrightarrow{d} denotes convergence in distribution.

In this paper, a CRP will be defined for multiset permutations and derived using the methods in [23]. As motivation, we note that multiset permutations are of fundamental interest in combinatorics [22] and random multiset permutations have been studied previously [10].

2 Multiset permutations and their factorisations into cycles

There are at least two different ways of defining cycles of multiset permutations [19, 22]. Knuth’s way [19] will be used in this paper. In this section, we summarise the discussion and results on multiset permutation factorisation taken from Section 5.1.2 of [19] that is needed in this paper. In particular, we are going to use Theorem 1 below to factor multiset permutations. A multiset is like a set except that it can have repetitions of identical elements, for example

$$M = \{1, 1, 1, 2, 2, 3, 4, 4, 4, 4\},$$

where the set $\{1, 2, 3, 4\}$ is given the usual ordering. A permutation of a multiset is an arrangement of its elements in a row, for example

$$3 \ 1 \ 2 \ 4 \ 4 \ 1 \ 2 \ 4 \ 1 \ 4.$$

We may write this in two-line notation as

$$\begin{pmatrix} 1 & 1 & 1 & 2 & 2 & 3 & 4 & 4 & 4 & 4 \\ 3 & 1 & 2 & 4 & 4 & 1 & 2 & 4 & 1 & 4 \end{pmatrix}. \tag{1}$$

The *intercalation product* $\pi_1 \perp \pi_2$ of two multiset permutations π_1 and π_2 is defined in [6, 11] and is obtained by

1. Expressing π_1 and π_2 in the two-line notation.
2. Juxtaposing these two-line notations.
3. Sorting the columns into nondecreasing order of the top line, in such a way that the sorting is stable, in the sense that left-to-right order in the bottom line is preserved when the corresponding top line elements are equal.

For example,

$$\begin{aligned} & \begin{pmatrix} 1 & 1 & 2 & 3 & 4 \\ 3 & 1 & 4 & 1 & 2 \end{pmatrix} \top \begin{pmatrix} 1 & 2 & 4 & 4 & 4 \\ 2 & 4 & 4 & 1 & 4 \end{pmatrix} \\ &= \begin{pmatrix} 1 & 1 & 1 & 2 & 2 & 3 & 4 & 4 & 4 & 4 \\ 3 & 1 & 2 & 4 & 4 & 1 & 2 & 4 & 1 & 4 \end{pmatrix} \end{aligned}$$

For possibly repeated elements x_1, x_2, \dots, x_m , the *cycle* (x_1, \dots, x_n) stands for the permutation obtained in two line form by sorting the columns of

$$\begin{pmatrix} x_1 & x_2 & \dots & x_m \\ x_2 & x_3 & \dots & x_1 \end{pmatrix}$$

in a stable manner. For example, we have

$$\begin{aligned} & (4\ 2\ 4\ 4\ 1\ 3\ 1\ 1\ 2\ 4) \\ &= \begin{pmatrix} 4 & 2 & 4 & 4 & 1 & 3 & 1 & 1 & 2 & 4 \\ 2 & 4 & 4 & 1 & 3 & 1 & 1 & 2 & 4 & 4 \end{pmatrix} \\ &= \begin{pmatrix} 1 & 1 & 1 & 2 & 2 & 3 & 4 & 4 & 4 & 4 \\ 3 & 1 & 2 & 4 & 4 & 1 & 2 & 4 & 1 & 4 \end{pmatrix} \end{aligned} \tag{2}$$

and so (1) is a cycle. For these general cycles, $(x_1x_2 \dots x_n)$ is not always the same as $(x_2 \dots x_nx_1)$ and it can happen that a cycle can be written as the intercalation product of other cycles, as we shall see at the end of this section.

Knuth [19] proves the following factorisation of multiset permutations into cycles.

Theorem 1 ([19]). *Let the elements of the multiset M be linearly ordered by the relation $<$. Every permutation π of M has a unique representation as the intercalation*

$$\pi = (x_{1,1} \dots x_{1,m_1}y_1) \top (x_{2,1} \dots x_{2,m_2}y_2) \top \dots \top (x_{\tau,1} \dots x_{\tau,n_\tau}y_\tau), \quad \tau \geq 1, \tag{3}$$

where the following two conditions are satisfied:

1. $y_1 \leq y_2 \leq \dots \leq y_\tau$

2. $y_i < x_{i,j}$ for $1 \leq j \leq m_i, 1 \leq i \leq \tau$.

Note that (2) is not in the form (3). The factorisation of (1) corresponding to Theorem 1 is

$$\begin{aligned} & (3\ 1) \top (1) \top (2\ 4\ 2\ 4\ 4\ 1) \top (4) \\ = & \begin{pmatrix} 3 & 1 \\ 1 & 3 \end{pmatrix} \top \begin{pmatrix} 1 \\ 1 \end{pmatrix} \top \begin{pmatrix} 2 & 4 & 2 & 4 & 4 & 1 \\ 4 & 2 & 4 & 4 & 1 & 2 \end{pmatrix} \top \begin{pmatrix} 4 \\ 4 \end{pmatrix} \\ = & \begin{pmatrix} 3 & 1 & 1 & 2 & 4 & 2 & 4 & 4 & 1 & 4 \\ 1 & 3 & 1 & 4 & 2 & 4 & 4 & 1 & 2 & 4 \end{pmatrix} \\ = & \begin{pmatrix} 1 & 1 & 1 & 2 & 2 & 3 & 4 & 4 & 4 & 4 \\ 3 & 1 & 2 & 4 & 4 & 1 & 2 & 4 & 1 & 4 \end{pmatrix}. \end{aligned}$$

3 The CRP for multiset permutations

Given a fixed sequence of positive integers $n_i \geq 1, i \geq 1$, we will construct a CRP process on permutations of multisets indexed by integers $t \geq 0$. We define $M(n_1, \dots, n_t)$ to be the multiset which contains n_i copies of i for $i \in [t], t \geq 1$, and \emptyset for $t = 0$. We give the set of elements $[t]$ of $M(n_1, \dots, n_t)$ the usual ordering. The set of permutations of $M(n_1, \dots, n_t)$ is denoted by $S(n_1, \dots, n_t)$ and is of size

$$|S(n_1, \dots, n_t)| = \binom{N_t}{n_1, \dots, n_t},$$

where $N_t = n_1 + \dots + n_t$. Note that $S_n = S(\underbrace{1, 1, \dots, 1}_{n \text{ times}})$. The random multiset permu-

tation $\tilde{\Pi}_t$ of our process at the t th step is an element of $S(n_1, \dots, n_t)$, represented in accordance with (3). At step $t \geq 1$, there are n_t copies of t either to be inserted in the existing permutation $\tilde{\Pi}_{t-1}$ or to be put into singleton cycles. (It is not possible to put more than one copy of t in a new cycle because of condition 2 of Theorem 1.) Suppose that $k_t \in \{0\} \cup [n_t]$ of the n_t copies of t start k_t new singleton cycles containing t , and the $n_t - k_t$ other copies of t are inserted into the existing permutation. The $n_t - k_t$ copies of t can be inserted to the left of any of the y_i or x_{ij} in (3). A ‘stars and bars’ argument shows that the number of ways of inserting $n_t - k_t$ copies of t to the left of an element in the multiset $S(n_1, \dots, n_{t-1})$ formatted like (3) is

$$\binom{N_{t-1} - 1 + n_t - k_t}{n_t - k_t}, \tag{4}$$

recalling that

$$\binom{-1}{k} = \begin{cases} 1 & \text{if } k = 0; \\ 0 & \text{if } k > 1. \end{cases}$$

We now define the multiset CRP. Given $\theta > 0$, define

$$F_t(\theta) = \sum_{k_t=0}^{n_t} \binom{N_{t-1} - 1 + n_t - k_t}{n_t - k_t} \theta^{k_t}$$

The special case

$$F_t(1) = \sum_{k_t=0}^{n_t} \binom{N_{t-1} - 1 + n_t - k_t}{n_t - k_t} = \binom{N_t}{n_t}. \tag{5}$$

results from the well known identity

$$\sum_{\rho=0}^{\nu} \binom{\mu + \rho}{\rho} = \binom{\mu + \nu + 1}{\nu}, \quad \nu, \mu \geq 0 \text{ integers}; \tag{6}$$

see page 161 of [15]. Note that (5) is the total number of ways of extending the permutation from time $t - 1$ to time t . At time $t \geq 1$, k_t new singleton cycles containing t are created and the other $n_t - k_t$ copies are inserted into the existing permutation in a specified way with probability $\theta^{k_t} / F_t(\theta)$. If $n_t = 1$ for all t , then $F_t(\theta) = \theta + t - 1$ and we recover the usual CRP. An induction argument on t shows that all possible $\pi \in S(n_1, \dots, n_t)$ can be constructed in this manner. This can also be seen from the identity

$$\binom{N_t}{n_1, \dots, n_t} = \prod_{s=1}^t \binom{N_s}{n_s}$$

Next we will find the distribution of $\tilde{\Pi}_t$.

Theorem 2. Given $\theta > 0$, for all $\pi \in S(n_1, \dots, n_t)$ the CRP generates π at step t with probability equal to $\theta^{|\pi|} / S$, where

$$S = \sum_{\pi \in S(n_1, \dots, n_t)} \theta^{|\pi|} = \prod_{s=1}^t F_s(\theta). \tag{7}$$

Proof. We will use the method in [23]. An *arborescence* is a directed, rooted tree with edges oriented in agreement with paths from the root to the leaves. Our arborescence has vertex set $V = \bigcup_{s=0}^t \Pi(n_1, \dots, n_s)$ and the root is \emptyset (when $s = 0$). The leaves of the arborescence are $\Pi(n_1, \dots, n_t)$. Give each leaf $\pi \in \Pi(n_1, \dots, n_t)$ the weight $\theta^{|\pi|}$, where $|\pi|$ is the number of cycles in π . There is a directed edge from $\pi_1 \in \Pi(n_1, \dots, n_{s-1})$ to $\pi_2 \in \Pi(n_1, \dots, n_s)$, $s \in [t]$, if and only if, for some $k_s \in \{0\} \cup [n_s]$, π_2 is obtained from π_1 by inserting $n_s - k_s$ copies of s to the left of elements of π_1 , when π_1 is written as (1), and creating k_s singleton cycles each containing s . For each $\pi \in V$, define $Q(\pi)$ to be the sum of the weights of all leaves $\pi' \in \Pi(n_1, \dots, n_t)$ for which there is a directed path from π to π' . For $\pi \in \Pi(n_1, \dots, n_s)$, we have

$$Q(\pi) = \theta^{|\pi|} \prod_{u=s+1}^t F_u(\theta), \tag{8}$$

which follows immediately from the interpretation of the binomial coefficient preceding (4). Taking $\pi = \emptyset$ and $s = 0$ in (8) gives (7). With π_1 and π_2 taken as above, we have $|\pi_2| = |\pi_1| + k_s$, and therefore

$$P_{\pi_1, \pi_2} := \frac{Q(\pi_2)}{Q(\pi_1)} = \frac{\theta^{k_s}}{F_s(\theta)}. \tag{9}$$

These are the transition probabilities of the CRP. Theorem 1 of [23] states that if we put transition probabilities (9) on the edges of the arborescence, and let the leaves be absorbing states, then we obtain a Markov chain whose probability of absorption on a given leaf is proportional to the weight of the leaf. By our choice of weight we are done. \square

For different steps the permutations are consistent, in the sense that $\tilde{\Pi}_s$, for $s < t$, can be derived from $\tilde{\Pi}_t$ by removing elements $s+1, \dots, t$ from their cycles and deleting empty cycles if necessary.

4 The distribution of the number of cycles

Let X_t denote the number of new cycles added in moving from time $t-1$ to time t , $t \geq 1$, which is the choice of k_t above. The X_t are independent with distributions given by

$$\mathbf{P}(X_t = k_t) = \frac{\theta^{k_t}}{F_t(\theta)} \binom{N_{t-1} - 1 + n_t - k_t}{n_t - k_t}, \quad k_t \in \{0\} \cup [n_t]. \quad (10)$$

If $\theta = 1$, then, by (5), we have

$$\mathbf{P}(X_t = k_t) = \frac{1}{\binom{N_t}{n_t}} \binom{N_{t-1} - 1 + n_t - k_t}{n_t - k_t} = \frac{\binom{n_t}{k_t}}{\binom{N_t}{k_t}} \frac{N_t - n_t}{N_t - k_t} \quad (11)$$

This equals the probability that starting from an urn with n_t balls representing failures and $N_t - n_t$ balls representing successes, that the first k_t balls pulled from the urn without replacement are failures, and the $(k_t + 1)$ th ball pulled from an urn is a success. This description shows that $Y_t = X_t + 1$ has a negative hypergeometric distribution, which we now describe. The negative hypergeometric distribution [17, 18, 21] with parameters N , M and r is like the negative binomial distribution, but without replacement. There are N balls in total, M balls representing success and $N - M$ balls representing failures. The hypergeometric distribution gives the probability that the r th success happens on the κ th draw, $\kappa = r, r+1, \dots, N$. A negative hypergeometric random variable Y with these parameters has probability mass function

$$\mathbb{P}(Y = \kappa) = \frac{\binom{M}{r-1} \binom{N-M}{\kappa-r}}{\binom{N}{\kappa-1}} \cdot \frac{M-r+1}{N-\kappa+1} \quad (12)$$

It is easily checked that (11) is (12) with $N = N_t$, $M = N_t - n_t = N_{t-1}$, $r = 1$ and $\kappa = k + 1$. The expectation of Y is

$$\mathbb{E}(Y) = r \frac{N+1}{M+1},$$

the variance of Y is

$$\text{Var}(Y) = \frac{r(N-M)(N+1)(M+1-r)}{(M+1)^2(M+2)}$$

and the third centred moment (see [17, 18]) is

$$\mathbb{E}([Y - \mathbb{E}(Y)]^3) = \text{Var}(Y) \cdot \frac{(2N - M + 1)(M + 1 - 2r)}{(M + 1)(M + 3)}.$$

Therefore,

$$\mathbb{E}(X_t) = \mathbb{E}(Y_t) - 1 = \frac{N_t + 1}{N_{t-1} + 1} - 1 = \frac{n_t}{N_{t-1} + 1}, \tag{13}$$

$$\text{Var}(X_t) = \text{Var}(Y_t) = \frac{n_t(N_t + 1)N_{t-1}}{(N_{t-1} + 1)^2(N_{t-1} + 2)} \tag{14}$$

and

$$\begin{aligned} \mathbb{E}([X_t - \mathbb{E}(X_t)]^3) &= \mathbb{E}([Y_t - \mathbb{E}(Y_t)]^3) \\ &= \text{Var}(Y_t) \cdot \frac{(n_t + N_t + 1)(N_{t-1} - 1)}{(N_{t-1} + 1)(N_{t-1} + 3)}. \end{aligned} \tag{15}$$

It follows that the number of cycles $K_t = \sum_{s=1}^t X_s$ has expectation

$$\mathbb{E}(K_t) = \sum_{s=1}^t \frac{n_s}{N_{s-1} + 1}$$

and variance

$$\text{Var}(K_t) = \sum_{s=1}^t \frac{n_s(N_s + 1)N_{s-1}}{(N_{s-1} + 1)^2(N_{s-1} + 2)}.$$

Given sequences a_t and b_t , we use the notation $a_t = O(b_t)$ to mean $a_t \leq Cb_t$ for a constant $C > 0$; $a_t \asymp b_t$ to mean $C_1b_t \leq a_t \leq C_2b_t$ for constants $C_1 > 0$, $C_2 > 0$; and $a_t \sim b_t$ to mean $\lim_{t \rightarrow \infty} a_t/b_t = 1$. We also define $a_t = o(b_t)$ to mean $\lim_{t \rightarrow \infty} a_t/b_t = 0$. We will put the bound the $n_t = O(1)$ to give a central limit theorem for K_t for all θ .

Theorem 3. *If $\theta = 1$ and $n_i = n \geq 1$ for all $i \geq 1$, then*

$$\mathbb{E}(K_t) \sim \log t, \quad \text{Var}(K_t) \sim \log t. \tag{16}$$

For general θ , let n_1, n_2, \dots , be given, $n_i \geq 1$ for all i , and suppose

$$n_i = O(1). \tag{17}$$

Then,

$$\mathbb{E}(K_t) \asymp \log t, \quad \text{Var}(K_t) \asymp \log t, \tag{18}$$

and

$$K_n \sim \mathbb{E}(K_n) \text{ a.s.}, \quad \frac{K_t - \mathbb{E}(K_t)}{\sqrt{\text{Var}(K_t)}} \xrightarrow{d} N(0, 1). \tag{19}$$

Proof. First we prove the theorem for $\theta = 1$. From (13), (14) and (17) we get $\mathbb{E}(X_t) \asymp 1/t$ and $\text{Var}(X_t) \asymp 1/t$, which result in (18), after which the Lindeberg-Feller Theorem easily shows the central limit theorem in (19), because $X_t \leq n_t = O(1)$. If we impose the condition $n_i = n$, for $i \geq 1$, then we immediately obtain (16). For θ general, we reduce to the case $\theta = 1$. This follows from noting that in (10), $\theta^{k_t} \asymp 1$ and $F_t(\theta) \asymp F_t(1)$ uniformly over $t \geq 1$, by (17), and so (18) still holds. For the almost sure convergence, modify the proof of (6.6) Theorem on page 44 of [8]. \square

By the following theorem a Central Limit Theorem can be obtained even when n_t is unbounded, which is not the case in Theorem 3.

Theorem 4. *Suppose $\theta = 1$, $n_t = O(N_{t-1})$. Then, (19) holds.*

Proof. In order to prove limiting normality, we will verify Lyapounov’s Condition in [3] with $\delta = 1$, by showing that

$$\lim_{t \rightarrow \infty} \frac{1}{\text{Var}(K_t)^{3/2}} \sum_{s=1}^t \mathbb{E}([X_s - \mathbb{E}(X_s)]^3) = 0. \tag{20}$$

The assumption $n_t = O(N_{t-1})$, (14) and (15) produces

$$\mathbb{E}([X_t - \mathbb{E}(X_t)]^3) \asymp \text{Var}(X_t) \asymp n_t/N_{t-1}, \quad t \geq 2.$$

We have the lower bound

$$\begin{aligned} \sum_{s=2}^t \frac{n_s}{N_{s-1}} &\geq \sum_{s=2}^t \ln \left(1 + \frac{n_s}{N_{s-1}} \right) \\ &= \sum_{s=2}^t (\ln(N_s) - \ln(N_{s-1})) \\ &= \ln(N_t) - \ln(N_1) \rightarrow \infty, \end{aligned}$$

where the convergence to infinity follows from the assumption $n_t \geq 1$ for all $t \geq 1$. Hence,

$$\text{Var}(K_t) \asymp \sum_{s=1}^t \mathbb{E}([X_s - \mathbb{E}(X_s)]^3) \asymp \sum_{s=2}^t \frac{n_s}{N_{s-1}} \rightarrow \infty$$

and (20) holds.

For the almost sure convergence, modify the proof of (6.6) Theorem on page 44 of [8] as in the proof of Theorem 3. \square

An example where Theorem 4 holds is obtained by setting $\theta = 1$, $n_t = \lceil Ct^\alpha \rceil$, for constants $C > 0$, $\alpha > 0$, where $\lceil x \rceil$ is the smallest integer greater or equal to x . Then, $n_t = Ct^\alpha + O(1)$ and $N_t = Ct^{\alpha+1}/(\alpha + 1) + O(t^\alpha)$ and the assumptions of Theorem 4 hold. The expectation and variance are asymptotically

$$\mathbb{E}(K_t) \sim (\alpha + 1) \log t, \quad \text{Var}(K_t) \sim (\alpha + 1) \log t.$$

Another example for $\theta = 1$ is obtained through regular variation [4]. A positive, measurable function $\ell(x)$, defined on $[\eta, \infty)$ for η real, is *slowly varying* if

$$\lim_{x \rightarrow \infty} \frac{\ell(\lambda x)}{\ell(x)} = 1, \quad \forall \lambda > 0. \tag{21}$$

The Uniform Convergence Theorem [4] provides that the convergence in (21) is uniform on compact λ -sets in $(0, \infty)$. A positive, measurable function defined on $[\eta, \infty)$, is *regularly varying* with real index α if

$$\lim_{x \rightarrow \infty} \frac{f(\lambda x)}{f(x)} = \lambda^\alpha, \quad \forall \lambda > 0.$$

A regularly varying function with index α can be written as

$$f(x) = x^\alpha \ell(x),$$

where $\ell(x)$ is a slowly varying function. Suppose that $\ell(x)$ is locally bounded in $[\eta, \infty)$, i.e. bounded on compact subsets of $[\eta, \infty)$, and $\alpha > -1$. Karamata's theorem gives

$$\int_\eta^t x^\alpha \ell(x) dx \sim t^{\alpha+1} \ell(t) / (\alpha + 1), \quad t \rightarrow \infty.$$

We further suppose that $\eta \leq 1$, $\alpha \geq 0$, with $\lim_{x \rightarrow \infty} \ell(x) = \infty$ in the case $\alpha = 0$, and define

$$n_t = \left\lceil \int_t^{t+1} x^\alpha \ell(x) dx \right\rceil, \quad t \geq 1.$$

The Uniform Convergence Theorem implies that

$$\sup_{t \leq x \leq t+1} \left| \frac{\ell(x)}{\ell(t)} - 1 \right| \leq \sup_{1 \leq \lambda \leq 2} \left| \frac{\ell(\lambda t)}{\ell(t)} - 1 \right| = o(1),$$

from which

$$\begin{aligned} \int_t^{t+1} x^\alpha \ell(x) dx &= (1 + o(1)) \ell(t) \int_t^{t+1} x^\alpha dx \\ &= (1 + o(1)) \ell(t) (t^\alpha + o(t^\alpha)) \end{aligned}$$

and

$$n_t \sim t^\alpha \ell(t).$$

Moreover, Karamata's theorem gives us

$$N_{t-1} \sim t^{\alpha+1} \ell(t) / (\alpha + 1).$$

Hence, the conditions of Theorem 4 hold.

We will now show that n_t may be chosen in such a way that the conclusion of the central limit theorem does not hold for K_t . Suppose that $\theta = 1$ and the n_t are chosen such that

$$N_{t-1} = o(n_t). \tag{22}$$

By (13) and (14), we have

$$\mathbb{E}(X_t) \sim \frac{n_t}{N_{t-1}}, \quad \text{Var}(X_t) \sim \left(\frac{n_t}{N_{t-1}} \right)^2.$$

We further choose the n_t such that

$$\sum_{s=1}^{t-1} \text{Var}(X_s) = o(\text{Var}(X_t)), \tag{23}$$

A particular example of such a sequence is

$$n_t = \lceil e^{t^3} \rceil = e^{t^3} + O(1),$$

from which

$$\begin{aligned}
 N_t &= \sum_{s=1}^t e^{s^3} + O(t) \\
 &= e^{t^3} \left(1 + \sum_{s=1}^{t-1} e^{s^3-t^3} \right) + O(t) \\
 &= e^{t^3} \left(1 + O\left(t e^{(t-1)^3-t^3} \right) \right) + O(t) \\
 &= e^{t^3} (1 + o(1)).
 \end{aligned}$$

Clearly, (22) holds and we also have

$$\begin{aligned}
 \sum_{s=1}^{t-1} \text{Var}(X_s) &= O\left(\sum_{s=1}^{t-1} e^{2s^3-2(s-1)^3} \right) \\
 &= O\left(\sum_{s=1}^{t-1} e^{6s^2-6s} \right) \\
 &= O\left(t e^{6(t-1)^2-6(t-1)} \right) \\
 &= o\left(e^{6t^2-6t} \right)
 \end{aligned}$$

and so (23) holds, as well, because $\text{Var}(X_t) \sim e^{6t^2-6t+2}$.

Assuming (22) and (23), we have

$$\frac{K_t - \mathbb{E}(K_t)}{\sqrt{\text{Var}(K_t)}} = \frac{X_t - \mathbb{E}(X_t)}{\sqrt{\text{Var}(X_t)}} (1 + o(1)) + \frac{\sum_{s=1}^{t-1} (X_s - \mathbb{E}(X_s))}{\sqrt{\text{Var}(K_t)}}. \tag{24}$$

Suppose that

$$\frac{K_t - \mathbb{E}(K_t)}{\sqrt{\text{Var}(K_t)}} \xrightarrow{d} N(0, 1).$$

By our assumptions, the variance of the last term of (24) is $o(1)$ and so by Slutsky’s theorem [8]

$$\lim_{t \rightarrow \infty} \mathbb{P} \left(\frac{X_t - \mathbb{E}(X_t)}{\sqrt{\text{Var}(K_t)}} \leq 0 \right) = \lim_{t \rightarrow \infty} \mathbb{P} \left(\frac{K_t - \mathbb{E}(K_t)}{\sqrt{\text{Var}(X_t)}} \leq 0 \right) = 1/2, \tag{25}$$

We will show that (25) is impossible. The c.d.f. of X_t is given by

$$\begin{aligned}
 P(X_t \leq x_t) &= \sum_{k_t=0}^{x_t} \mathbb{P}(X_t = k_t) \\
 &= \frac{1}{\binom{N_t}{n_t}} \sum_{k_t=0}^{x_t} \binom{N_{t-1} - 1 + n_t - k_t}{n_t - k_t}
 \end{aligned} \tag{26}$$

$$\begin{aligned}
 &= \frac{1}{\binom{N_t}{n_t}} \left(\sum_{j=0}^{n_t} \binom{N_{t-1} - 1 + j}{j} - \sum_{j=0}^{n_t - x_t - 1} \binom{N_{t-1} - 1 + j}{j} \right) \\
 &= \frac{1}{\binom{N_t}{n_t}} \left(\binom{N_t}{n_t} - \binom{N_t - x_t - 1}{n_t - x_t - 1} \right) \tag{27}
 \end{aligned}$$

$$\begin{aligned}
 &= 1 - \frac{(N_t - x_t - 1)! / (n_t - x_t - 1)!}{N_t! / n_t!} \\
 &\geq 1 - \left(\frac{N_t - x_t - 1}{N_t} \right)^{N_{t-1}}, \tag{28}
 \end{aligned}$$

where we have used (11) at (26), (6) at (27), and $(N_t - x_t - 1 - i) / (N_t - i) \leq (N_t - x_t - 1) / N_t$ for all $0 \leq i \leq N_{t-1} - 1$ at (28). We therefore have

$$\begin{aligned}
 \liminf_{t \rightarrow \infty} P(X_t \leq \mathbb{E}(X_t)) &\geq 1 - \lim_{t \rightarrow \infty} \left(\frac{N_t - \mathbb{E}(X_t) - 1}{N_t} \right)^{N_{t-1}} \\
 &= 1 - \lim_{t \rightarrow \infty} \left(\frac{N_t - n_t(1 + o(1)) / N_{t-1} - 1}{N_t} \right)^{N_{t-1}} \\
 &= 1 - \lim_{t \rightarrow \infty} (1 - (1 + o(1)) / N_{t-1})^{N_{t-1}} \\
 &= 1 - e^{-1} > 1/2,
 \end{aligned}$$

contradicting (25).

5 Discussion

Potentially, improvements might be made on these results. The CRP we have defined places all n_t elements labelled t at the same time. Placing them sequentially seems like a difficult problem. It would be interesting to get better estimates for $\mathbb{E}(K_t)$ and $\text{Var}(K_t)$, especially when $\theta \neq 1$. Perhaps the hypotheses of Theorem 4 could be weakened.

In the case of random permutations, there is a Poisson approximation of K_n . The total variation distance between the law $\mathcal{L}(K_n)$ of K_n and the $\text{Poisson}(\mathbb{E}(K_n))$ distribution is of order

$$\begin{aligned}
 d_{\text{TV}}(\mathcal{L}(K_n), \text{Poisson}(\mathbb{E}(K_n))) &:= \frac{1}{2} \sum_{k=1}^n \left| \mathbb{P}(K_n = k) - \exp(-\mathbb{E}(K_n)) \frac{\mathbb{E}(K_n)^k}{k!} \right| \\
 &\asymp \frac{1}{\log n};
 \end{aligned}$$

see [2]. By considering the process of cycle counts $(C_1(n), C_2(n), \dots, C_n(n))$, where $C_i(n)$ is the number of cycles of size i , we may write $K_n = \sum_{i=1}^n C_i(n)$. Moreover, [7] shows that $B_n(\cdot) \xrightarrow{d} B(\cdot)$, where

$$B_n(t) := \frac{\sum_{i=1}^{\lfloor n^t \rfloor} C_i(n) - t \log n}{\sqrt{\log n}}, \quad 0 \leq t \leq 1,$$

and $B(t)$ is standard Brownian motion. If suitable approximations could be made to the process of cycle counts for multiset permutations, then similar progress might be made for the results obtained in this paper when $\theta = 1$.

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