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Response to the reviewer comments

1. I've replaced "length of the longest head run" with "longest run" as suggested by the reviewer.
2. I've added "{\xi_{k}=1} represents failure of the *k*th component" as suggested by the reviewer.
3. The text on page 2 states "N_n(k) of head runs with lengths ≥*k*".
4. Statistics & Probability Letters is among journals cited in the manuscript.

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On the length of the longest head run

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Abstract

We evaluate the accuracy of approximation to the distribution of the length of the longest head run in a Markov chain with a discrete state space. An estimate of the accuracy of approximation in terms of the total variation distance is established for the first time.

Key words: longest head run, extremes in samples of random size.
AMS Subject Classification: 60E15, 60G70.

1 Introduction

Let $\{\xi_i, i \geq 1\}$ be a sequence of random 0's and 1's (i.e., "tails" and "heads"). Then

$$L_n = \max\{k : \xi_{i+1} = ... = \xi_{i+k} = 1 \quad (\exists i \leq n-k)\} \tag{1}$$

is the length of the longest head run (LLHR) among $\xi_1, ..., \xi_n$.

Statistic L_n has applications in biology, reliability theory, finance, and nonparametric statistics (see, e.g., [1, 2, 3, 17]). In particular, the reliability of a consecutive k-out-of-n system with n components can be expressed via $\mathbb{P}(L_n < k)$, where the event $\{\xi_k = 1\}$ represents failure of the kth component: the system fails if and only if k consecutive components fail [1, 4, 6, 13].

The study of the distribution of LLHR has a long history. Apparently, the task was first formulated by de Moivre [10], Problem LXXIV. Renewed interest to the topic arose in connection with the Erdös–Rényi strong law of large numbers [5].

A limit theorem for LLHR in the case of independent Bernoulli $\mathbf{B}(p)$ trials was established by Goncharov [8]. The limiting distribution of LLHR was found in more general situations as well, see [1, 12, 14, 19] and references therein. In particular, a limit theorem for LLHR in a Markov chain with a finite state space $\mathcal{X}$ where hitting a subset of $\mathcal{X}$ is considered a "success" is given in [12]. An estimate of the rate of convergence and asymptotic expansions in the limit theorem for LLHR in a two-state Markov chain have been established in [13]. Concerning LIL-type results, see [16] and references therein.

An exact formula for $\mathbb{P}(L_n < k)$ in terms of combinatorial coefficients in the case of independent Bernoulli trials was found by Uspensky [18]. In the case of a two-state Markov chain Fe et al. [6] present an exact formula for $\mathbb{P}(L_n < k)$ in terms of a specially constructed matrix of transition probabilities, and establish the asymptotics of $\ln \mathbb{P}(L_n < k)$ as $n \to \infty$ if k is fixed (see also Theorem 2 in [13]).

Note that L_n can be represented as a sample maximum in a sample of random size ν_n, where ν_n is a certain renewal process (cf. [13, 14]). References concerning extremes in samples of random size can be found, e.g., in [7, 9, 16].

It is known that the accuracy of approximation to the distribution of LLHR in terms of the uniform distance is $n^{-1}\ln n$ [13]. The result has been generalised to the case of a Markov chain with a finite state space [14] as well as to the case of m-dependent random variables [15]. Asymptotic expansions in the limit theorem for LLHR in a two-state Markov chain [13] confirm that the rate $n^{-1}\ln n$ cannot be improved.

There is a simple relation between LLHR and the number $N_n(k)$ of head runs with lengths $\geq k$:

$$\{L_n < k\} = \{N_n(k) = 0\}.$$

Note that the estimates of the accuracy of approximation to the distribution of $N_n(k)$ have been established in terms of the total variation distance (see [1, 2, 16] and references therein). However, the problem of evaluating the accuracy of approximation to the distribution of LLHR in terms of the total variation distance remained open for a long while.

In this paper we derive an estimate of order $n^{-1}\ln n$ to the total variation distance between $\mathcal{L}(L_n)$ and the approximating distribution.

2 Results

Let $\{X_i, i \geq 1\}$ be a homogeneous Markov chain with a finite state space $\mathcal{X}$ and transition probabilities $\|p_{ij}\|_{i,j\in\mathcal{X}}$. We denote by

$$\bar{\pi} = \|\pi_i\|_{i\in\mathcal{X}}$$

the stationary distribution of the chain.

Given a subset $A \subset \mathcal{X}$, let LLHR be defined by (1), where

$$\xi_i = \mathbb{1}\{X_i \in A\}$$

(hitting A is considered a "success"). We set

$$U = \|p_{ij}\|_{i,j\in A}\,, \quad \bar{\pi}_A = \|\pi_i\|_{i\in A}\,,$$

and let

$$q(k) = \bar{\pi}_A U^{k-1}(E-U)\bar{1} \quad (k \geq 1),$$

where $\bar{1}$ is a vector of 1's and E is a unit diagonal matrix.

Let ζ_n, Z_n be random variables (r.v.s) with distribution functions (d.f.s)

$$\mathbb{P}(\zeta_n < k) = (1-q(k))^{n-k}\,, \ \mathbb{P}(Z_n < k) = \exp(-nq(k)) \qquad (k \geq 1).$$

Recall the definition of the total variation distance between the distributions of r.v.s X and Y:

$$d_{TV}(X;Y) \equiv d_{TV}(\mathcal{L}(X);\mathcal{L}(Y)) = \sup_{A\in\mathcal{A}} |\mathbb{P}(X \in A) - \mathbb{P}(Y \in A)|\,,$$

where $\mathcal{A}$ is a Borel σ-field.

The distribution of LLHR L_n can be well approximated by $\mathcal{L}(\zeta_n)$ or $\mathcal{L}(Z_n)$; the accuracy of such approximation in terms of the uniform distance is known to be of order $n^{-1}\ln n$. In Theorem 1 below we show that the result holds in terms of the stronger total variation distance.

Theorem 1 *Assume that*

(P0) there is only one class C of essential states that consists of periodic subclasses $C_1, ..., C_d$;

(P1) $A \cap C_i \neq \varnothing$ $(1 \leq i \leq d)$;

(P2) $0<\lambda<1$, *where* λ *is the largest eigenvalue of matrix* U*;*
(P3) if $i\in C_\ell$ *for some* $\ell\in\{1,...,d\}$*, then*

$$|p_{ij}(m)-d\pi_j|\le u_m\,,\ \ H:=\sum_{m\ge1}u_m<\infty \tag{2}$$

if $j\in A\cap C_k$ *and* $k-m=\ell\ (\mathrm{mod}\,d)$*; if* $i\notin C_1\cup...\cup C_d$*, then* (2) *holds for all* $j\in A$*;*
(P4) $z_i>0$ *(*$\forall i\in A$*), where* $\bar z=\|z_i\|_{i\in A}$ *is the corresponding to* λ *right eigenvector of matrix* U*.*
Then there exists a positive constant $C=C(\lambda,\bar z,\bar\pi_A)$ *such that*

$$d_{TV}(L_n;Z_n)\le Cn^{-1}\ln n \qquad (n\ge C). \tag{3}$$

The result holds if Z_n *in (3) is replaced with* ζ_n*.*

3 Proofs

Proof of Theorem 1 makes use of Theorem 2 from [14], which is presented below (note that the argument of Theorem 2 in [14] is valid for any fixed $d\in\mathbb{N}$). In the particular case of a stationary Markov chain the result of Theorem 2 is given by Theorem 2.1 in [12].

Theorem 2 *Let* $\{X_i,i\ge1\}$ *be a homogeneous Markov chain with a discrete state space* $\mathcal{X}$*, transition probabilities* $\|p_{ij}\|_{i,j\in\mathcal{X}}$ *and stationary distribution* $\bar\pi$*. Assume conditions P(0) – P(4). Then there exists a positive constant* $c_\star=c_\star(\lambda,\bar z,\bar\pi_A)$ *such that as* $n>2k\ge c_\star$*,*

$$\begin{aligned}&|\mathbb{P}(L_n<k)-\mathbb{P}(Z_n<k)|\\&\le c_\star\lambda^k+c_\star k\lambda^k\exp\Big(-nq(k)(1-c_\star k\lambda^k)\Big)\,.\end{aligned} \tag{4}$$

Taking into account the obvious inequality

$$|e^x-e^y|\le|x-y|e^{\max\{x;y\}} \qquad (x,y\in\mathbb{R}), \tag{5}$$

we notice that (4) holds true if Z_n is replaced with ζ_n.

In the case of independent observations inequalities of this kind with explicit constants are presented in [15, 11]. In the case of a two-state Markov chain with

$\alpha := p_{11} \in (0;1)$, $\beta := p_{00} < 1$, a sharp bound of this kind is given in [13], Theorem 2: there exist constants $q \in (0;1)$, $C < \infty$ such that

$$\sup_{k>C} \left| \mathbb{P}(L_n < k) - A(t_0)/t_0^{n+1} \right| \leq Cq^n \tag{6}$$

for particular t_0 and function $A(t)$ obeying $|A(t_0)-1| \leq C_1\gamma k\alpha^k$, $|t_0 - 1 - \gamma\alpha^k| \leq C_1 k(\gamma\alpha^k)^2$ for some $C_1 < \infty$, where $\gamma = (1-\alpha)(1-\beta)/\alpha(2-\alpha-\beta)$. In the case of independent Bernoulli $\mathbf{B}(\alpha)$ trials (6) holds with $q = \alpha$, $C = (2+\alpha-\alpha^2)/(1-\alpha)(1-\alpha^2)$.

By a well-known property of the total variation distance,

$$2d_{TV}(L_n; Z_n) = \sum_{k\geq 0} |\mathbb{P}(L_n = k) - \mathbb{P}(Z_n = k)|. \tag{7}$$

The idea of the prof is to split the sum in (7) into appropriate fragments and show that the desired estimate holds for each fragment.

Recall that $\bar{\pi}_A = \|\pi_i\|_{i\in A}$, and set

$$\begin{aligned} c_* &= <\bar{\pi}_A; \bar{z}>(1-\lambda)/\lambda z^*, \quad c^* = <\bar{\pi}_A; \bar{z}>(1-\lambda)/\lambda z_*, \\ \bar{z}_* &= \inf\{z_j : j \in A\}, \qquad \bar{z}^* = \sup\{z_j : j \in A\}. \end{aligned}$$

Note that

$$0 < c_* \leq c^* < \infty.$$

It is easy to see that

$$c_*\lambda^k \leq q(k) \leq c^*\lambda^k \tag{8}$$

(cf. (8) in [14]). Let

$$k(n) = \log n - \log\ln n + \log(c_*/2).$$

Hereinafter $\log$ is to the base $1/\lambda$, symbol c (with or without indexes) denotes positive constants.

Using (4) and (8), we check that

$$\begin{aligned} &\sum_{k\leq k(n)} |\mathbb{P}(L_n = k) - \mathbb{P}(Z_n = k)| \\ &\leq \mathbb{P}(L_n \leq k(n)) + \mathbb{P}(Z_n \leq k(n)) \leq c_1 n^{-1}\ln n. \end{aligned} \tag{9}$$

It remains to evaluate

$$\sum_{k>k(n)} |\mathbb{P}(L_n\!=\!k) - \mathbb{P}(Z_n\!=\!k)|.$$

According to (4) and (8), there exists a positive constant c_2 such that

$$|\mathbb{P}(L_n\!=\!k) - \mathbb{P}(Z_n\!=\!k)| \le c_2\lambda^k + c_2 k\lambda^k e^{-n\lambda^k c_*/2} \tag{10}$$

as $n\!>\!2k\!\ge\!c_2$. Evidently,

$$\sum_{k>k(n)} \lambda^k \le \lambda^{k(n)}/(1\!-\!\lambda) = 2n^{-1}(\ln n)/(1\!-\!\lambda)c_*. \tag{11}$$

Thus, it remains to evaluate $\sum_{k>k(n)} k\lambda^k e^{-n\lambda^k c_*/2}$.

Note that function $f(x) = xe^{-x}$ decreases in $[1;\infty)$. Clearly, $n\lambda^k c_*/2 \in [1;\ln n]$ as $k(n)\!<\!k\!<\!\log(nc_*/2)$. Therefore,

$$\begin{aligned}\sum_{k(n)<k<\log(nc_*/2)} k\lambda^k e^{-n\lambda^k c_*/2} &\le n^{-1}\log(nc_*/2) \sum_{k(n)<k<\log(nc_*/2)} n\lambda^k e^{-n\lambda^k c_*/2} \\ &\le n^{-1}\log(nc_*/2) \int_{k(n)}^{\log(nc_*/2)} n\lambda^x e^{-n\lambda^x c_*/2} dx \\ &\le 2n^{-1}\log(nc_*/2)/\ln(1/\lambda)c_*. \end{aligned} \tag{12}$$

Since

$$\sum_{k\ge m} k\lambda^k \le m\lambda^m/(1\!-\!\lambda)^2 \qquad (m\!\ge\!1),$$

we have

$$\sum_{k\ge\log(nc_*/2)} k\lambda^k e^{-n\lambda^k c_*/2} \le \sum_{k\ge\log(nc_*/2)} k\lambda^k \le 2\lceil\log(nc_*/2)\rceil/nc_*(1\!-\!\lambda)^2\,, \tag{13}$$

where $\lceil x \rceil$ denotes the smallest integer greater than or equal to x.

Combining estimates (9) – (13), we derive (3). The proof is complete. □

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