Partial Fillup and Search Time in LC Tries

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Abstract

Andersson and Nilsson introduced in 1993 a *level-compressed trie* (in short: LC trie) in which a full subtree of a node is compressed to a single node of degree being the size of the subtree. Recent experimental results indicated a "dramatic improvement" when full subtrees are replaced by "partially filled subtrees". In this paper, we provide a theoretical justification of these experimental results showing, among others, a rather moderate improvement of the search time over the original LC tries. For such an analysis, we assume that n strings are generated independently by a binary memoryless source (a generalization to Markov sources is possible) with p denoting the probability of emitting a "1" (and $q = 1-p$). We first prove that the so called α-fillup level $F_n(\alpha)$ (i.e., the largest level in a trie with α fraction of nodes present at this level) is concentrated on two values whp (with high probability); either $F_n(\alpha) = k_n$ or $F_n(\alpha) = k_n + 1$ where $k_n = \log_{\frac{1}{\sqrt{pq}}} n - \frac{|\ln(p/q)|}{2\ln^{3/2}(1/\sqrt{pq})}\Phi^{-1}(\alpha)\sqrt{\ln n} + O(1)$ is an integer and $\Phi(x)$ denotes the normal distribution function. This result directly yields the typical depth (search time) $D_n(\alpha)$ in the α-LC tries with $p \neq 1/2$, namely we show that whp $D_n(\alpha) \sim C_1 \log\log n$ where $C_1 = 1/|\log(1-h/\log(1/\sqrt{pq}))|$ and $h = -p\log p - q\log q$ is the Shannon entropy rate. This should be compared with recently found typical depth in the original LC tries which is $C_2 \log\log n$ where $C_2 = 1/|\log(1-h/\log(1/\min\{p, 1-p\}))|$. In conclusion, we observe that α affects only the lower term of the α-fillup level $F_n(\alpha)$, and the search time in α-LC tries is of the same order as in the original LC tries.

Key Words: Digital trees, level-compressed tries, partial fillup, probabilistic analysis, poissonization.

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1 Introduction

Tries and suffix trees are the most popular data structures on words [7]. A *trie* is a digital tree built over, say n, strings (the reader is referred to [12, 14, 25] for an in depth discussion of digital trees.) A string is stored in an external node of a trie and the path length to such a node is the shortest prefix of the string that is not a prefix of any other strings (cf. Figure 1). Throughout, we assume a binary alphabet. Then each branching node in a trie is a binary node. A special case of a trie structure is a *suffix trie* (tree) which is a trie built over suffixes of a *single* string.

Since 1960 tries were used in many computer science applications such as searching and sorting, dynamic hashing, conflict resolution algorithms, leader election algorithms, IP addresses lookup, coding, polynomial factorization, Lempel-Ziv compression schemes, and molecular biology. For example, in the internet IP addresses lookup problem [15, 23] one needs a fast algorithm that directs an incoming packet with a given IP address to its destination. As a matter of fact, this is the *longest matching prefix* problem, and standard tries are well suited for it. However, the search time is too large. If there are n IP addresses in the database, the search time is $O(\log n)$, and this is not acceptable. In order to improve the search time, Andersson and Nilsson [1, 15] introduced a novel data structure called the *level compressed trie* or in short LC trie (cf. Figure 1). In the LC trie we replace the root with a node of degree equal to the size of the largest *full subtree* emanating from the root (the depth of such a subtree is called the *fillup level*). This is further carried on recursively throughout the whole trie (cf. Figure 1).

Some recent experimental results reported in [8, 18, 17] indicated a "dramatic improvement" in the search time when full subtrees are replaced by "partially fillup subtrees". In this paper, we provide a theoretical justification of these experimental results by considering α-LC tries in which one replaces a subtree with the last level only α-filled by a node of degree equal to the size of such a subtree (and we continue recursively). In order to understand theoretically the α-LC trie behavior, we study here the so called *α-fillup* level $F_n(\alpha)$ and the *typical depth* or the search time $D_n(\alpha)$. The α-fillup level is the last level in a trie that is α-filled, i.e. filled up to a fraction at least α (e.g., in a binary trie level k is α-filled if it contains $\alpha 2^k$ nodes). The typical depth is the length of a path from the root to a randomly selected external node; thus it represents the typical search time. In this paper we analyze the α-fillup level and the typical depth in an α-LC trie in a probabilistic framework when all strings are generated by a memoryless source with $\mathbb{P}(1) = p$ and $\mathbb{P}(0) = q := 1 - p$. Among other results, we prove that the α-LC trie shows a rather moderate improvement over the original LC tries. We shall quantify this statement below.

Tries were analyzed over the last thirty years for memoryless and Markov sources (cf. [2, 9, 11, 12, 14, 19, 20, 24, 25]). Pittel [19, 20] found the typical value of the fillup level F_n (i.e., $\alpha = 1$) in a trie built over n strings generated by mixing sources; for memoryless sources with high probability (whp)

$$F_n \overset{\text{p}}{\sim} \frac{\log n}{\log(1/p_{\min})} = \frac{\log n}{h_{-\infty}}$$

where $p_{\min} = \min\{p, 1-p\}$ is the smallest probability of generating a symbol and $h_{-\infty} = \log(1/p_{\min})$ is the Rényi entropy of infinite order (cf. [25]). We let $\log := \log_2$. In the above, we write $F_n \overset{\text{p}}{\sim} a_n$ to denote $F_n/a_n \to 1$ in probability, that is, for any $\varepsilon > 0$ we have $\mathbb{P}((1-\varepsilon)a_n \le F_n \le (1+\varepsilon)a_n) \to 1$ as $n \to \infty$.

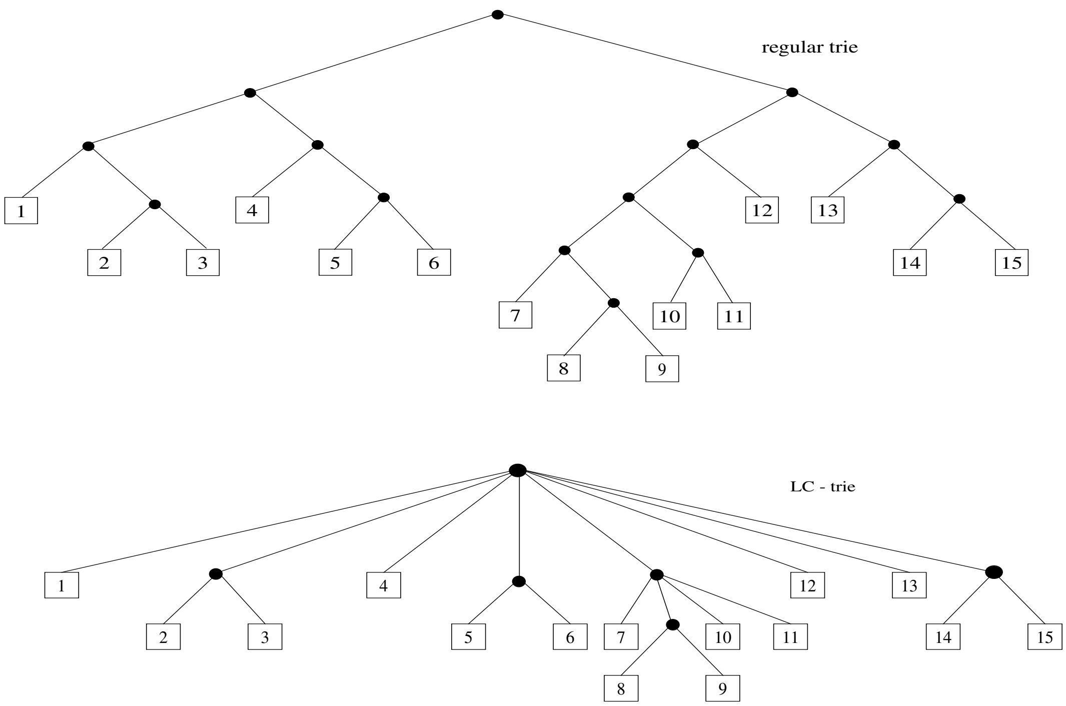

Figure 1: A trie and its associated full LC trie.

This was further extended by Devroye [2], and Knessl and Szpankowski [11] who, among other results, proved that the fillup level F_n is concentrated on two points k_n and $k_n + 1$, where k_n is an integer

$$\frac{1}{\log p_{\min}^{-1}} (\log n - \log\log\log n) + O(1) \tag{1}$$

for $p \neq 1/2$. The depth in regular tries was analyzed by many authors who proved that whp the depth is about $(1/h)\log n$ (where $h = -p\log p - (1-p)\log(1-p)$ is the Shannon entropy rate of the source) and that it is normally distributed when $p \neq 1/2$ [20, 25].

The original LC tries were analyzed by Andersson and Nilsson [1] for unbiased memoryless source and by Devroye [3] for memoryless sources (cf. also [21, 22]). The typical depth (search time) for regular LC tries was only studied recently by Devroye and Szpankowski [4] who proved that for memoryless sources with $p \neq 1/2$

$$D_n \overset{\mathrm{p}}{\sim} \frac{\log\log n}{-\log\left(1 - h/h_{-\infty}\right)}. \tag{2}$$

In this paper we shall prove some rather surprising results. First of all, for $0 < \alpha < 1$ we show that the α-fillup level $F_n(\alpha)$ is whp equal either to k_n or $k_n + 1$ where

$$k_n = \log_{\frac{1}{\sqrt{pq}}} n - \frac{|\ln(p/q)|}{2\ln^{3/2}(1/\sqrt{pq})} \Phi^{-1}(\alpha)\sqrt{\ln n} + O(1). \tag{3}$$

As a consequence, we find that if $p \neq 1/2$, the depth $D_n(\alpha)$ of the α-LC is for large n typically about

$$\frac{\log\log n}{-\log\left(1 - h/\log(1/\sqrt{pq})\right)}.$$

The (full) 1-fillup level F_n shown in (1) should be compared to the α-fillup level $F_n(\alpha)$ presented in (3). Observe that the leading term of $F_n(\alpha)$ is *not* the same as the leading term of F_n when $p \neq 1/2$. Furthermore, α contributes only to the second term asymptotics. When comparing the typical depths D_n and $D_n(\alpha)$ we conclude that both grow like $\log\log n$ with two constants that do not differ by much. This comparison led us to a statement in the abstract that the improvement of α-LC tries over the regular LC tries is rather moderate. We may add that for relatively slowly growing functions such as $\log\log n$ the constants in front of them do matter (even for large values of n) and perhaps this led the authors of [8, 17, 18] to their statements.

The paper is organized as follows. In the next section we present our main results which are proved in the next two sections. We first consider a poissonized version of the problem for which we establish our findings. Then we show how to depoissonize our results completing our proof.

2 Main Results

Consider tries created by inserting n random strings of 0 and 1. We will always assume that the strings are (potentially) infinite and that the bits in the strings are independent random bits, with $\mathbb{P}(1) = p$ and thus $\mathbb{P}(0) = q := 1 - p$; moreover we assume that different strings are independent.

We let $X_k := \#\{\text{internal nodes filled at level } k\}$ and $\overline{X}_k := X_k/2^k$, i.e. the proportion of nodes filled at level k. Note that X_k may both increase and decrease as k grows, while

$$1 \geq \overline{X}_k \geq \overline{X}_{k+1} \geq 0.$$

Recall that the fillup level of the trie is defined as the last full level, i.e. $\max\{k : \overline{X}_k = 1\}$, while the height is the last level with any nodes at all, i.e. $\max\{k : \overline{X}_k > 0\}$. Similarly, if $0 < \alpha \leq 1$, the α-fillup level $F_n(\alpha)$ is the last level where at least a proportion α of the nodes are filled, i.e.

$$F_n(\alpha) = \max\{k : \overline{X}_k \geq \alpha\}.$$

We will in this paper study the α-fillup level for a given α with $0 < \alpha < 1$ and a given p with $0 < p < 1$.

We have the following result, where whp means with probability tending to 1 as $n \to \infty$, and Φ denotes the normal distribution function. Theorem 1 is proved in Section 4, after first considering a Poissonized version in Section 3.

Theorem 1. *Let α and p be fixed with $0 < \alpha < 1$ and $0 < p < 1$, and let $F_n(\alpha)$ be the α-fillup level for the trie formed by n random strings as above. Then, for each n there is an integer*

$$k_n = \log_{\frac{1}{\sqrt{pq}}} n - \frac{|\ln(p/q)|}{2\ln^{3/2}(1/\sqrt{pq})}\Phi^{-1}(\alpha)\sqrt{\ln n} + O(1)$$

such that whp $F_n(\alpha) = k_n$ or $k_n + 1$. Moreover, $\mathbf{E}\,\overline{X}_{k_n} = \alpha + O(1/\sqrt{\log n})$ for $p \neq 1/2$.

Thus the α-fillup level $F_n(\alpha)$ is concentrated on at most two values; as in many similar situations (cf. [2, 11, 19, 25]), it is easily seen from the proof that in fact for most n it is concentrated on a single value k_n, but there are transitional regimes, close to the values of n where k_n changes, where $F_n(\alpha)$ takes two values with comparable probabilities.

Note that when $p = 1/2$, the second term on the right hand side disappears, and thus simply $k_n = \log n + O(1)$; in particular, two different values of $\alpha \in (0, 1)$ have their corresponding k_n differing by $O(1)$ only. When $p \neq 1/2$, changing α means shifting k_n by $\Theta(\log^{1/2} n)$. By Theorem 1, whp $F_n(\alpha)$ is shifted by the same amounts.

To the first order, we thus have the following simple result.

Corollary 2. *For any fixed α and p with $0 < \alpha < 1$ and $0 < p < 1$,*

$$F_n(\alpha) = \log_{\frac{1}{\sqrt{pq}}} n + O_p(\sqrt{\ln n});$$

in particular, $F_n(\alpha)/\log_{1/\sqrt{pq}} n \xrightarrow{\mathrm{p}} 1$ as $n \to \infty$.

Surprisingly enough, the leading terms of the fillup level for $\alpha = 1$ and $\alpha < 1$ are quantitatively different for $p \neq 1/2$. It is well known, as explained in the introduction, that the regular fillup level F_n is concentrated on two points around $\log n/\log(1/p_{\min})$, while the partial fillup level $F_n(\alpha)$ concentrates around $k_n \sim \log n/\log(1/\sqrt{pq})$. Secondly, the leading term of $F_n(\alpha)$ does not depend on α and the second term is proportional to $\sqrt{\log n}$, while for the regular fillup level F_n the second term is of order $\log\log\log n$.

Theorem 1 yields several consequences for the behavior of α-LC tries. In particular, it implies the typical behavior of the depth, that is, the search time. Below we formulate our main second result concerning the depth for α-LC tries delaying the proof to Section 5; cf. (2) and [4, 22] for LC tries.

Theorem 3. *For any fixed $0 < \alpha < 1$ and $p \neq 1/2$ we have*

$$D_n(\alpha) \overset{\mathrm{p}}{\sim} \frac{\log\log n}{-\log\left(1 - \frac{h}{\log(1/\sqrt{pq})}\right)} \tag{4}$$

as $n \to \infty$ where $h = -p\log p - (1-p)\log(1-p)$ is the entropy rate of the source.

As a direct consequence of Theorem 3 we can numerically quantify experimental results recently reported in [17] where a "dramatic improvement" in the search time of α-LC tries over the regular LC tries was observed. In a regular LC trie the search time is $O(\log\log n)$ with the constant in front of $\log\log n$ being $1/\log(1 - h/\log(1/p_{\min}))^{-1}$ [4]. For α-LC tries this constant decreases to $1/\log(1-h/\log(1/\sqrt{pq}))^{-1}$. While it is hardly a "dramatic improvement", the fact that we deal with a slowly growing leading term $\log\log n$, may indeed lead to experimentally observed significant changes in the search time.

3 Poissonization

In this section we consider a Poissonized version of the problem, where there are $\mathrm{Po}(\lambda)$ strings inserted in the trie. We let $\tilde{F}_\lambda(\alpha)$ denote the α-fillup level of this trie.

Theorem 4. *Let α and p be fixed with $0 < \alpha < 1$ and $0 < p < 1$, and let $\tilde{F}_\lambda(\alpha)$ be the α-fillup level for the trie formed by $\mathrm{Po}(\lambda)$ random strings as above. Then, for each $\lambda > 0$ there is an integer*

$$k_\lambda = \log_{\frac{1}{\sqrt{pq}}} \lambda - \frac{|\ln(p/q)|}{2\ln^{3/2}(1/\sqrt{pq})}\Phi^{-1}(\alpha)\sqrt{\ln\lambda} + O(1) \tag{5}$$

such that whp (as $\lambda \to \infty$) $\tilde{F}_\lambda(\alpha) = k_\lambda$ or $k_\lambda + 1$.

We shall prove Theorem 4 through a series of lemmas. Observe first that a node at level k can be labeled by a binary string of length k, and that the node is filled if and only if at least two of the inserted strings begin with this label. For $r \in \{0,1\}^k$, let $N_1(r)$ be the number of ones in r, and let $P(r) = p^{N_1(r)} q^{k-N_1(r)}$ be the probability that a random string begins with r. Then, in the Poissonized version, the number of inserted strings beginning with $r \in \{0,1\}^k$ has a Poisson distribution $\mathrm{Po}(\lambda P(r))$, and these numbers are independent for different strings r of the same length. Consequently,

$$X_k = \sum_{r \in \{0,1\}^k} I_r \tag{6}$$

where I_r are independent indicators with

$$\mathbb{P}(I_r = 1) = \mathbb{P}(\mathrm{Po}(\lambda P(r)) \geq 2) = 1 - (1 + \lambda P(r)) e^{-\lambda P(r)}. \tag{7}$$

Hence,

$$\mathbf{Var}\,(X_k) = \sum_{r \in \{0,1\}^k} P(I_r = 1)\big(1 - P(I_r = 1)\big) < 2^k$$

so $\mathbf{Var}\,(\overline{X}_k) < 2^{-k}$ and, by Chebyshev's inequality,

$$\mathbb{P}(|\overline{X}_k - \mathbf{E}\,\overline{X}_k| > 2^{-k/3}) \to 0. \tag{8}$$

Consequently, $\overline{X}_k$ is sharply concentrated, and it is enough to study its expectation. (It is straightforward to calculate $\mathbf{Var}\,(X_k)$ more precisely, and to obtain a normal limit theorem for X_k, but we do not need that.)

Assume first $p > 1/2$.

Lemma 1. *If* $p > 1/2$ *and*

$$k = \log_{\frac{1}{\sqrt{pq}}} \lambda - \frac{\ln(p/q)}{2 \ln^{3/2}(1/\sqrt{pq})} \Phi^{-1}(\alpha) \sqrt{\ln \lambda} + O(1), \tag{9}$$

then $\mathbf{E}\,\overline{X}_k = \alpha + O(k^{-1/2})$.

Proof. Let $\rho = p/q > 1$ and define γ by $\lambda p^\gamma q^{k-\gamma} = 1$, i.e.,

$$\rho^\gamma = \left(\frac{p}{q}\right)^\gamma = \lambda^{-1} q^{-k},$$

which leads to

$$\gamma = \frac{k \ln(1/q) - \ln \lambda}{\ln(p/q)}. \tag{10}$$

Let $\mu_j = \lambda p^j q^{k-j} = \rho^{j-\gamma}$. By (6) and (7),

$$\mathbf{E}\,\overline{X}_k = 2^{-k} \sum_{j=0}^{k} \binom{k}{j} \mathbb{P}(\mathrm{Po}(\mu_j) \geq 2). \tag{11}$$

If $j < \gamma$, then $\mu_j < 1$ and

$$\mathbb{P}(\mathrm{Po}(\mu_j) \geq 2) < \mu_j^2 < \mu_j.$$

If $j \ge \gamma$, then $\mu_j \ge 1$ and

$$1 - \mathbb{P}(\mathrm{Po}(\mu_j) \ge 2) = (1+\mu_j)e^{-\mu_j} \le 2\mu_j e^{-\mu_j} < 4\mu_j^{-1}.$$

Hence (11) yields, using $\binom{k}{j} \le \binom{k}{\lfloor k/2 \rfloor} = O(2^k k^{-1/2})$,

$$\begin{aligned}
\mathbf{E}\,\overline{X}_k &= 2^{-k}\sum_{j<\gamma}\binom{k}{j}O(\mu_j) + 2^{-k}\sum_{j\ge\gamma}\binom{k}{j}(1-O(\mu_j^{-1})) \\
&= 2^{-k}\sum_{j\ge\gamma}\binom{k}{j} + 2^{-k}\sum_{j=0}^{k}\binom{k}{j}O(\rho^{-|j-\gamma|}) \\
&= \mathbb{P}\bigl(\mathrm{Bi}(k,1/2) \ge \gamma\bigr) + O(k^{-1/2}).
\end{aligned} \tag{12}$$

By the Berry–Esseen theorem [6, Theorem XVI.5.1],

$$\mathbb{P}(\mathrm{Bi}(k,1/2) \ge \gamma) = 1 - \Phi\Bigl(\frac{\gamma - k/2}{\sqrt{k/4}}\Bigr) + O(k^{-1/2}). \tag{13}$$

By (10) and the assumption (9),

$$\begin{aligned}
\gamma - \frac{k}{2} &= \frac{1}{\ln(p/q)}\left(k\ln\frac{1}{q} - \ln\lambda - \frac{k}{2}\ln\frac{p}{q}\right) \\
&= \frac{1}{\ln(p/q)}\left(k\ln\frac{1}{\sqrt{pq}} - \ln\lambda\right) \\
&= \frac{\ln(1/\sqrt{pq})}{\ln(p/q)}\left(k - \log_{1/\sqrt{pq}}\lambda\right) \\
&= -\tfrac{1}{2}(\ln(1/\sqrt{pq}))^{-1/2}\Phi^{-1}(\alpha)\sqrt{\ln\lambda} + O(1) \\
&= -\tfrac{1}{2}\Phi^{-1}(\alpha)k^{1/2} + O(1).
\end{aligned} \tag{14}$$

This finally implies

$$1 - \Phi\Bigl(\frac{\gamma - k/2}{\sqrt{k/4}}\Bigr) = 1 - \Phi(-\Phi^{-1}(\alpha)) + O(k^{-1/2}) = \alpha + O(k^{-1/2}),$$

and the lemma follows by (12) and (13). ∎

Lemma 2. *Fix $p > 1/2$. For every $A > 0$, there exists $c > 0$ such that if $|k - \log_{1/\sqrt{pq}}\lambda| \le Ak^{1/2}$, then $\mathbf{E}\,\overline{X}_k - \mathbf{E}\,\overline{X}_{k+1} > ck^{-1/2}$.*

Proof. A string $r \in \{0,1\}^k$ has two extensions $r0$ and $r1$ in $\{0,1\}^{k+1}$. Clearly, $I_{r0}, I_{r1} \le I_r$, and if there are exactly 2 (or 3) of the inserted strings beginning with r, then $I_{r0} + I_{r1} \le 1 < 2I_r$. Hence

$$\mathbf{E}\,(2X_k - X_{k+1}) = \sum_{r\in\{0,1\}^k}\mathbf{E}\,(2I_r - I_{r0} - I_{r1}) \ge \sum_{r\in\{0,1\}^k}\mathbb{P}\bigl(\mathrm{Po}(\lambda P(r)) = 2\bigr). \tag{15}$$

Let ρ and γ be as in the proof of Lemma 1, and let $j = \lceil\gamma\rceil$. Then $\mu_j = \rho^{j-\gamma} \in [1,\rho]$ and thus $\mathbb{P}(\mathrm{Po}(\mu_j) = 2) \ge \frac{1}{2}e^{-\rho}$. Moreover, by (14) and the assumption,

$$|j - k/2| \le \frac{\ln(1/\sqrt{pq})}{\ln(p/q)}Ak^{1/2} + 1 = O(k^{1/2}).$$

Thus, if k is large enough, we have by the standard normal approximation of the binomial probabilities (which follows easily from Stirling's formula, as found already by de Moivre [5])

$$2^{-k}\binom{k}{j} = \frac{1+o(1)}{\sqrt{2\pi k/4}} e^{-2(j-k/2)^2/k} \geq c_1 k^{-1/2}$$

for some $c_1 > 0$. Hence, by (15),

$$\mathbf{E}\,\overline{X}_k - \mathbf{E}\,\overline{X}_{k+1} = 2^{-k-1}\mathbf{E}\,(2X_k - X_{k+1}) \geq 2^{-k-1}\binom{k}{j}\mathbb{P}(\mathrm{Po}(\mu_j) = 2) \geq \frac{c_1 e^{-\rho}}{4} k^{-1/2}$$

as needed. $\square$

Now assume $p > 1/2$. Starting with any k as in (9), we can by Lemmas 1 and 2 shift k up or down $O(1)$ steps and find k_λ as in (5) such that, for a suitable $c > 0$, $\mathbf{E}\,\overline{X}_{k_\lambda} \geq \alpha + \frac{1}{2}ck_\lambda^{-1/2} > \mathbf{E}\,\overline{X}_{k_\lambda+1}$ and $\mathbf{E}\,\overline{X}_{k_\lambda+2} \leq \mathbf{E}\,\overline{X}_{k_\lambda+1} - ck_\lambda^{-1/2} < \alpha - \frac{1}{2}ck_\lambda^{-1/2}$. It follows by (8) that whp $\overline{X}_{k_\lambda} \geq \alpha$ and $\overline{X}_{k_\lambda+2} < \alpha$, and hence $\tilde{F}_\lambda(\alpha) = k_\lambda$ or $k_\lambda + 1$.

This proves Theorem 4 in the case $p > 1/2$. The case $p < 1/2$ follows by symmetry, interchanging p and q.

In the remaining case $p = 1/2$, all $P(r) = 2^{-k}$ are equal. Thus, by (6) and (7),

$$\mathbf{E}\,\overline{X}_k = \mathbb{P}(\mathrm{Po}(\lambda 2^{-k}) \geq 2). \tag{16}$$

Given $\alpha \in (0,1)$, there is a $\mu > 0$ such that $\mathbb{P}(\mathrm{Po}(\mu) \geq 2) = \alpha$. We take $k_\lambda = \lfloor \log(\lambda/\mu) - 1/2 \rfloor$. Then, $\lambda 2^{-k_\lambda} \geq 2^{1/2}\mu$ and thus $\mathbf{E}\,\overline{X}_{k_\lambda} \geq \alpha_+$ for some $\alpha_+ > \alpha$. Similarly, $\mathbf{E}\,\overline{X}_{k_\lambda+2} \leq \alpha_-$ for some $\alpha_- < \alpha$, and the result follows in this case too.

4 Depoissonization

To complete the proof of Theorem 1 we must depoissonize the results obtained in Theorem 4, which we do in this section.

Proof of Theorem 1. Given an integer n, let k_n be as in the proof of Theorem 4 with $\lambda = n$, and let $\lambda_\pm = n \pm n^{2/3}$. Then $\mathbb{P}(\mathrm{Po}(\lambda_-) \leq n)) \to 1$ and $\mathbb{P}(\mathrm{Po}(\lambda_+) \geq n)) \to 1$ as $n \to \infty$. By monotonicity, we thus have whp $\tilde{F}_{\lambda_-}(\alpha) \leq F_n(\alpha) \leq \tilde{F}_{\lambda_+}(\alpha)$, and by Theorem 4 it remains only to show that we can take $k_{\lambda_-} = k_{\lambda_+} = k_n$.

Let us now write $X_k(\lambda)$ and $\overline{X}_k(\lambda)$, since we are working with several λ.

Lemma 3. *Assume $p \neq 1/2$. Then, for every k,*

$$\frac{d}{d\lambda}\mathbf{E}\,\overline{X}_k(\lambda) = O(\lambda^{-1}k^{-1/2}).$$

Proof. We have

$$\frac{d}{d\mu}\mathbb{P}(\mathrm{Po}(\mu) \geq 2) = \frac{d}{d\mu}((1-(1+\mu)e^{-\mu}) = \mu e^{-\mu}$$

and thus, by (11) and the argument in (12),

$$\begin{aligned}\frac{d}{d\lambda}\mathbf{E}\,\overline{X}_k(\lambda) &= 2^{-k}\sum_{j=0}^{k}\binom{k}{j}\mu_j e^{-\mu_j}\frac{d\mu_j}{d\lambda}\\ &= \lambda^{-1}2^{-k}\sum_{j=0}^{k}\binom{k}{j}\mu_j^2 e^{-\mu_j} = O\Big(\lambda^{-1}\sum_{j=0}^{k}2^{-k}\binom{k}{j}\min(\mu_j,\mu_j^{-1})\Big)\\ &= O(\lambda^{-1}k^{-1/2})\end{aligned}$$

which completes the proof. □

By Lemma 3, $|\mathbf{E}\,\overline{X}_k(\lambda_\pm) - \mathbf{E}\,\overline{X}_k(n)| = O(n^{-1/3}k^{-1/2}) = o(k^{-1/2})$. Hence, by the proof of Theorem 4, for large n, $\mathbf{E}\,\overline{X}_{k_n}(\lambda_\pm) \geq \alpha + \frac{1}{3}ck_n^{-1/2}$ and $\mathbf{E}\,\overline{X}_{k_n+2}(\lambda_\pm) < \alpha - \frac{1}{3}ck_n^{-1/2}$, and thus whp $\tilde{F}_{\lambda_\pm}(\alpha) = k_n$ or $k_n + 1$. Moreover, the estimate $\mathbf{E}\,\overline{X}_{k_n} = \alpha + O(1/\sqrt{\log n})$ follows easily from the similar estimate for the Poisson version in Lemma 1; we omit the details. This completes the proof of Theorem 1 for $p > 1/2$. The case $p < 1/2$ is again the same by symmetry. The proof when $p = 1/2$ is similar, now using (16). □

5 Proof of Theorem 3

First, let us explain heuristically our estimate for $D_n(\alpha)$. By the Asymptotic Equipartition Property (cf. [25]) at level k_n there are about $n2^{-hk_n}$ strings with the same prefix of length k_n as a randomly chosen one, where h is the entropy. That is, in the corresponding branch of the α-LC trie, we have about $n2^{-hk_n} \approx n^{1-h/b}$ strings (or external nodes), where for simplicity $b = \log(1/\sqrt{pq})$. In the next level, we shall have about $n^{(1-h/b)^2}$ external nodes, and so on. In particular, at level $D_n(\alpha)$ we have approximately

$$n^{(1-h/b)^{D_n(\alpha)}}$$

external nodes. Setting this $= \Theta(1)$ leads to our estimate (4) of Theorem 3.

We now make this argument rigorous. We construct an α-LC trie from n random strings $\xi_1, \dots, \xi_n$ and look at the depth $D_n(\alpha)$ of a designated one of them. In principle, the designated string should be chosen at random, but by symmetry, we can assume that it is the first string ξ_1.

To construct the α-LC trie, we scan the strings $\xi_1, \dots, \xi_n$ in parallel one bit at a time, and build a trie level by level. As soon as the last level is filled less than α, we stop; we are now at level $F_n(\alpha) + 1$, just past the α-fillup level. The trie above this level, i.e. up to level $F_n(\alpha)$, is compressed into one node, and we continue recursively with the strings attached to each node at level $F_n(\alpha) + 1$ in the uncompressed trie, i.e. the sets of strings that begin with the same prefixes of length $F_n(\alpha) + 1$.

To find the depth $D_n(\alpha)$ of the designated string ξ_1 in the compressed trie, we may ignore all branches not containing ξ_1; thus we let Y_n be the number of the n strings that agree with ξ_1 for the first $F_n(\alpha) + 1$ bits. Note that we have not yet inspected any later bits. Hence, conditioned on $F_n(\alpha)$ and Y_n, the remaining parts of these Y_n strings are again i.i.d. random strings from the same memoryless source, so we may argue by recursion. The depth $D_n(\alpha)$ equals the number of recursions needed to reduce the number of strings to 1.

We begin by analysing a single step in the recursion. Let, for notational convenience, $\kappa := h/\log(1/\sqrt{pq})$. Note that $0 < \kappa < 1$.

Lemma 4. *Let $\varepsilon > 0$. Then, with probability $1 - O\big(n^{-\Theta(1)}\big)$,*

$$1 - \kappa - \varepsilon < \frac{\ln Y_n}{\ln n} < 1 - \kappa + \varepsilon. \tag{17}$$

We postpone the proof of Lemma 4, and first use it to complete the proof of Theorem 3. We assume below that n is large enough when needed, and that $0 < \varepsilon < \min(\kappa, 1-\kappa)/2$.

We iterate, and let Z_j be the number of strings remaining after j iterations; this is the number of strings that share the first j levels with ξ_1 in the compressed trie. We have $Z_0 = n$ and $Z_1 = Y_n$. We stop the iteration when there are less than $\ln n$ strings remaining; we thus let τ be the smallest integer such that $Z_\tau < \ln n$. In each iteration before τ, (17) holds with error probability $O\big((\ln n)^{-\Theta(1)}\big) = O\big((\ln\ln n)^{-2}\big)$. Hence, for any constant B, we have whp for every $j \le \min(\tau, B \ln\ln n)$, with $\kappa_\pm = \kappa \pm \varepsilon \in (0,1)$,

$$1 - \kappa_+ < \frac{\ln Z_j}{\ln Z_{j-1}} < 1 - \kappa_-,$$

or equivalently

$$\ln(1-\kappa_+) < \ln\ln Z_j - \ln\ln Z_{j-1} < \ln(1-\kappa_-). \tag{18}$$

If $\tau > \tau_+ := \lceil \ln\ln n / \ln(1-\kappa_-)^{-1} \rceil$, we find whp from (18)

$$\ln\ln Z_{\tau_+} \le \ln\ln Z_0 + \tau_+ \ln(1-\kappa_-) \le 0,$$

so $Z_{\tau_+} \le e < \ln n$, which violates $\tau > \tau_+$. Hence, $\tau \le \tau_+$ whp.

On the other hand, if $\tau < \tau_- := \lfloor (1-\varepsilon)\ln\ln n / \ln(1-\kappa_+)^{-1} \rfloor$, then whp by (18)

$$\ln\ln Z_\tau \ge \ln\ln Z_0 + \tau_- \ln(1-\kappa_+) \ge \varepsilon \ln\ln n,$$

which contradicts $\ln\ln Z_\tau < \ln\ln\ln n$.

Consequently, whp $\tau_- \le \tau \le \tau_+$; in other words, we need $\frac{\ln\ln n}{-\ln(1-\kappa)}\big(1 + O(\varepsilon)\big)$ iterations to reduce the number of strings to less than $\ln n$.

Iterating this result once, we see that whp at most $O(\ln\ln\ln n)$ further iterations are needed to reduce the number to less than $\ln\ln n$. Finally, the remaining depth then whp is $O(\ln\ln\ln n)$ even without compression. Hence we see that whp

$$D_n(\alpha) = \frac{\ln\ln n}{-\ln(1-\kappa)}\big(1 + O(\varepsilon)\big) + O(\ln\ln\ln n).$$

Since ε is arbitrary, Theorem 3 follows.

It remains to prove Lemma 4. Let W_k be the number of the strings $\xi_1, \dots, \xi_n$ that are equal to ξ_1 for at least their first k bits. The $Y_n = W_{F_n(\alpha)+1}$, and thus, for any $A > 0$,

$$\begin{aligned}\mathbb{P}\big(|\log Y_n - (1-\kappa)\log n| \ge 2\varepsilon \log n\big) &\le \mathbb{P}\big(|F_n(\alpha) - \log_{1/\sqrt{pq}} n| \ge A\sqrt{\ln n}\big) \\ &+ \sum_{|k-1-\log_{1/\sqrt{pq}} n| < A\sqrt{\ln n}} \mathbb{P}\big(|\log W_k - \log n + h \log_{1/\sqrt{pq}} n| \ge 2\varepsilon \log n\big).\end{aligned}$$

Lemma 4 thus follows from the following two lemmas, using the observation that $0 < 1/\log(1/\sqrt{pq}) < 1/h$.

The first lemma is a large deviation estimate corresponding to Corollary 2.

Lemma 5. *For each $\alpha \in (0,1)$, there exists a constant A such that*

$$\mathbb{P}\big(|F_n(\alpha) - \log_{1/\sqrt{pq}} n| \geq A\sqrt{\ln n}\big) = O(1/n).$$

Proof. We begin with the poissonized version, with $\mathrm{Po}(\lambda)$ strings as in Section 3. Let $k_\pm = k_\pm(\lambda) := \lfloor \log_{1/\sqrt{pq}} \lambda \pm A\sqrt{\ln \lambda} \rfloor$, and let δ be fixed with $0 < \delta < \min(\alpha, 1-\alpha)$. Then, by Lemma 1, if A is large enough, $\mathbf{E}\,\overline{X}_{k_-} > \alpha + \delta$ and $\mathbf{E}\,\overline{X}_{k_+} < \alpha - \delta$ for all large λ. By a Chernoff bound, (8) can be sharpened to

$$\mathbb{P}\big(|\overline{X}_k - \mathbf{E}\,\overline{X}_k| > \delta\big) = O\big(e^{-\Theta(2^k)}\big)$$

and thus

$$\begin{aligned}\mathbb{P}\big(\tilde{F}_\lambda(\alpha) < k_-\big) &\leq \mathbb{P}\big(\overline{X}_{k_-} < \alpha\big) \leq \mathbb{P}\big(\overline{X}_{k_-} - \mathbf{E}\,\overline{X}_{k_-} < -\delta\big) \\ &= O\Big(e^{-\Theta(2^{k_-})}\Big) = O\Big(e^{-\Theta(\lambda^{O(1)})}\Big) = O(\lambda^{-1}).\end{aligned}$$

Similarly, $\mathbb{P}(\tilde{F}_\lambda(\alpha) > k_+) = O(\lambda^{-1})$.

To depoissonize, let $\lambda_\pm = n \pm n^{2/3}$ as in Section 4 and note that, again by a Chernoff estimate, $\mathbb{P}\big(\mathrm{Po}(\lambda_-) \leq n\big) = O(n^{-1})$ and $\mathbb{P}\big(\mathrm{Po}(\lambda_+) \geq n\big) = O(n^{-1})$. Thus, with probability $1 - O(1/n)$,

$$k_-(\lambda_-) \leq \tilde{F}_{\lambda_-}(\alpha) \leq F_n(\alpha) \leq \tilde{F}_{\lambda_+}(\alpha) \leq k_+(\lambda_+),$$

and the result follows (if we increase A). ∎

Lemma 6. *Lat $0 < a < b < 1/h$ and $\varepsilon > 0$. Then, uniformly for all k with $a \log n \leq k \leq b \log n$,*

$$\mathbb{P}\big(|\log W_k - \log n + kh| > \varepsilon \log n\big) = O\big(n^{-\Theta(1)}\big). \tag{19}$$

Proof. Let N_1 be the number of 1's in the first k bits of ξ_1. Given N_1, the distribution of $W_k - 1$ is $\mathrm{Bi}(n-1, p^{N_1} q^{k-N_1})$.

Since $p^p q^q = 2^{-h}$, there exists $\delta > 0$ such that if $|N_1/k - p| \leq \delta$, then $2^{-h-\varepsilon} \leq p^{N_1/k} q^{1-N_1/k} \leq 2^{-h+\varepsilon}$, and thus

$$2^{-hk-\varepsilon k} \leq p^{N_1} q^{k-N_1} \leq 2^{-hk+\varepsilon k}, \qquad \text{when } |N_1/k - p| \leq \delta. \tag{20}$$

Noting that $hk \leq bh \log n$ and $bh < 1$, we see that, provided ε is small enough, $n 2^{-hk-\varepsilon k} \geq n^\eta$ for some $\eta > 0$, and then (20) and a Chernoff estimate yields, when $|N_1/k - p| \leq \delta$,

$$\mathbb{P}\big(\tfrac{1}{2} n 2^{-hk-\varepsilon k} \leq W_k \leq 2n 2^{-hk-\varepsilon k} \mid N_1\big) = 1 - O\big(e^{-\Theta(n^\eta)}\big) = 1 - O\big(n^{-1}\big),$$

and thus

$$\mathbb{P}\big(|\log W_k - \log n + hk| > \varepsilon k + 1 \mid N_1\big) = O\big(n^{-1}\big), \qquad \text{when } |N_1/k - p| \leq \delta. \tag{21}$$

Moreover, $N_1 \sim \mathrm{Bi}(k, p)$, so by another Chernoff estimate,

$$\mathbb{P}\big(|N_1/k - p| > \delta\big) = O\big(e^{-\Theta(k)}\big) = O\big(n^{-\Theta(1)}\big).$$

The result follows (possibly changing ε) from this and (21). ∎

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