A probabilistic analysis of a leader election algorithm

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A *leader election* algorithm is an elimination process that divides recursively into tow subgroups an initial group of n items, eliminates one subgroup and continues the procedure until a subgroup is of size 1. In this paper the biased case is analyzed. We are interested in the *cost* of the algorithm, *i.e.* the number of operations needed until the algorithm stops. Using a probabilistic approach, the asymptotic behavior of the algorithm is shown to be related to the behavior of a hitting time of two random sequences on $[0, 1]$.

Keywords: Election Algorithm. Randomized Selection Algorithm. Distributed Systems. Asymptotic Oscillating Behavior. Probabilistic de-Poissonization.

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Contents

1 Introduction

A single-hop network is a distributed system of n nodes, also called *stations*, sharing a common communication channel which can transmit only one message per time unit. In the special case of *collision* detection, the channel is ternary feedback; each station sending a message to the network can simultaneously listen to the channel and detect: a *collision* when at least there are two broadcast attempts, a *silence* when no station sends message, or a *success* when exactly one station sends its message. A single-hop network with *collision* detection is called *multiple access channel*.

Consider a *multiple access channel* of n stations which has to elect a *leader* to control and organize the network. Because of links or stations failures, the *leader* may be temporarily out of service. Such failure can be detected by a *silence*, in which case the system stops normal operations and initiates the *election* process: the system has to identify a new *leader* in a reasonable execution time. We are interested in the *cost* of the algorithm, i.e. the number of operations needed to find a *leader*.

1.1 Leader election problem

We assume that the size n of the *multiple access channel* is unknown. Moreover, each station is assumed to have a unique identifying number ID. To elect a *leader* among themselves, stations have to use the same algorithm. The case $n \in \{0, 1\}$ is trivial, n is assumed to be greater than 2. Let us recall the basic one:

— Deterministic Initialization: At the first time unit, each station send a message with its ID number to the common channel. As $n \geq 2$, all stations detect a *collision*.

— Randomized Selection Process: Each station S generates independently a *Bernoulli* random variable B_S with parameter p. Only which obtains $B_S = 1$ is allowed to send its message again during the next time unit.

For a station S, there are two cases:

1. If $B_S = 1$, station S will be called *Active*; S sends again its message to the channel and can detect
   — a *success*; only station S is trying transmission, then all the other stations receive its ID's message and S obtains the status of *leader*. The protocol is finished.
   — a *collision*; station S is not the only candidate to be *leader*, and so has to generate B_S again.

2. Otherwise, station S becomes *Non Active*; it remains candidate to be *leader*, listens to the channel but does not participate to the transmission. So it can detect

   — a *success*; only one station $S' \neq S$ is trying transmission. The other stations (including S) detect its ID. So S' obtains the status of *leader*. The protocol is finished.

   — a *collision*; although station S is not participating to the selection process, there are at least 2 *Active* stations. So, station S is eliminated.

   — a *silence*; all stations are *Non Active*, so station S has to generate B_S again to send or not its ID's message to the channel.

That is, at the end of the protocol, a single station remains *Active* and becomes the *leader* of the system.

This *splitting* process using a *Bernoulli* random variable was also used in the *tree protocol* of Capetanakis and Tsybakhov. For a survey, see Mathys and Flajolet (1985).

The example below illustrates the election process applied to a group of 4 stations $\{A, B, C, D\}$. In this case, the *leader* A is elected in 4 times units.

time units	1	2	3	4
Active Stations	A B C D	A B C		A
Non Active Stations		D	A B C	B C
Eliminated Stations			D	D
Channel feedback	*Collision*	*Collision*	*Silence*	*Success*

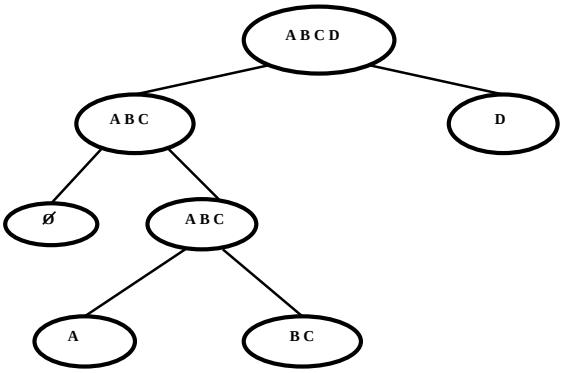


Fig. 1: Election of the *leader* A; $H_4 = 4$. Incomplete tree structure.

Definition 1 (Algorithm Cost) *It is the number of rounds needed to find a* leader. *Denote by H_n the algorithm cost when the size of the network is n.*

Such a randomized elimination algorithm has various applications in distributed systems like cellular phones and wireless communication networks. In mobile Ad-hoc networks, failures occur when mobile nodes move out of transmission range. The unstable topology of the network makes *leader election*

problem more complex. For more details, see Malpani et al. (2000). Electing a *leader* in a computer network is fundamental to supervise communication and synchronization. See Fill et al. (1996). It is also studied in a context of radio networks. For an interesting survey on randomized communication in this context, see Chlebus (2001). For more elaborate *leader election* algorithms on radio network with no *collision* detection, see Lavault et al. (2003).

1.2 Splitting process and tree structure

Formally, the algorithm starts with a group of n items which is divided in two subgroups. The probability that an item is sent into the left subgroup is p. This subgroup will be divided by the same process. The other items will be ignored. If the left subgroup is empty, the algorithm restarts from the previous level.

This distributed algorithm is a randomized elimination process with a natural binary tree structure (Fig.1). At the root of the associated tree, is the initial group of items. In the first split, it generates two nodes: the left one will be split by the same process, the right one is a terminal node, also called *leaf*, which will not be treated by the algorithm except when the left node is empty. Only in this case, the right node will be split into two one.

Thus, this tree structure can be represented as an incomplete tree in which only one side is developed. We define the *height* of the associated tree as the length of the path from the root to the *leader* which is the longest *root-to-leaf* path in the tree (see Fill et al. (1996)). Then the algorithm *cost* is equivalently the *height* of the associated tree. Fig.1 illustrates this equality.

1.3 Previous works

It is known that the average *cost* of the *leader election* algorithm is of logarithmic order in n with an oscillating behavior. See Prodinger (1993) for the unbiased case $p = 1/2$, Janson and Szpankowski (1997) for the biased one $p \neq 1/2$.

Consider the *Poisson* model of the *leader election* problem, i.e. the *election* process applied to a network with random size following a *Poisson* process $\mathcal{N}_x$ (see 1.6). Let h the *Poisson transform* of the sequence of average *cost* of the algorithm $(\mathbb{E}(H_n))_{n\geq 0}$.

Definition 2 (*Poisson transform)* *For $x > 0$, the Poisson transform of the sequence $(\mathbb{E}(H_n))$ is the function h defined by*

$$h(x) = \mathbb{E}(H_{\mathcal{N}_x}) = \sum_{n=2}^{+\infty} \mathbb{E}(H_n) \frac{x^n}{n!}\, e^{-x}.$$

Then, function h is solution of a functional equation, called *basic functional equation* associated to the algorithm

$$h(x) = h(px) + h(qx)\, e^{-px} + f(x), \quad \text{where } p + q = 1 \tag{1}$$

and f is a given function. Equation (1) is the starting point of all studies made on this algorithm.

The unbiased case

When the splitting process follows a *Bernoulli* random variable of parameter $1/2$, the *leader election* algorithm is called *symmetrical*. Observe that, for the unbiased case, the *functional equation* (**??**) is solved by direct iteration. In fact, the *Poisson transform* h verifies

$$h(x) = h(x/2)\left(1 + e^{-x/2}\right) + f(x),$$

which can be rewritten $g(x) = g(x/2) + f(x)/(1 - e^{-x})$ where $g(x) = h(x)/\left(1 - e^{-x}\right)$.

The first analysis of the *leader election* algorithm was proposed by Prodinger (1993). He investigated different parameters of interest such as the *height*, called *depth* in his paper, the *size* of the associated tree, *i.e.* the number of nodes.... Using combinatorial techniques, he established exact expressions and asymptotic formulas for these quantities for the symmetrical case. So, it is shown that for an initial group of size n, the algorithm stops on average after about $\log_2 n$ steps. Using complex analysis techniques like Mellin and inverse Mellin transform, Fill et al. (1996) studied the asymptotic behavior of the first two moments of the algorithm *cost*. Moreover, they obtained the exact expression and asymptotic behavior of the distribution of H_n and they have shown that a limit distribution for the centered algorithm *cost* $H_n - \lfloor \log_2 n \rfloor$ does not exist. For a survey on Mellin transform, see Flajolet et al. (1995).

The biased case

If the splitting process is biased, *i.e.* the probability that an item is sent into the left subgroup is $p \neq 1/2$, the algorithm is called *asymmetrical*. Studies on biased case become more rare. An asymmetric *leader election* algorithm was investigated by Janson and Szpankowski (1997) using complex analysis techniques. The asymptotic behavior of the first two moments of the algorithm *cost* H_n is given in term of the sequence of their exact values $\left(\mathbb{E}(H_j)\right)_{j\in\mathbb{N}}$ computed numerically from two recurrence equations.

This implicit dependence is due to the asymmetry of the functional equation (**??**) obtained by Poissonization. The coefficient $e^{-p\,x}$ makes more complex the establishment of an iterative scheme such as in the context of a protocol for a multi-access broadcast channel (see Fayolle et al. (1986)). Applying the Mellin transform to equation (**??**) without solving it yields this dependence.

1.4 Related leader election algorithms

Leader election algorithm in network of fixed size

Consider a simple algorithm for *leader election* algorithm in the context of communication network; at each level, the probability p for a station to send its message depends on the number n of stations remaining in the elimination process; $p = 1/n$. Expected run time is $O(1)$ but it is clear that is necessary to know the number of active stations in advance, or at least to estimate it. See Willard (1984) for an estimation procedure in order of $\log\log n + O(1/n)$. This variant of the basic *leader election* algorithm does not exhibit an oscillating behavior any more. In fact, the average algorithm cost is asymptotically equivalent to a some constant L. For more details, see Lavault and Louchard (2005).

LZ'77 data compression Scheme

Consider a variant of the *leader election* algorithm by introducing a moderator who determines the elimination process; each of participants and the moderator throws independently a coin and only those who obtain the same result as the moderator continue the process. See Ward and Szpankowski (2004) for the biased case, Prodinger (1993) for the unbiased one. Let M_n the number of participants remaining in the last nontrivial round from an initial group of n items. It is asymptotically equivalent to the multiplicity of phrases in the LZ'77 data compression scheme.

1.5 Overview

In a previous paper on *splitting* algorithms, Mohamed and Robert (2005) proposed a direct approach based on a probabilistic reformulation of a basic functional equation associated to such algorithms. The

purpose of this work is to apply the techniques used by Mohamed and Robert (2005) to analyze an additive quantity in the context of an incomplete tree structure. In Section 2, a similar series formula for the average *cost* $E(H_n)$ is given by Proposition 2. The asymptotic behavior of the algorithm is studied in Section 3 and reformulated on the behavior of some stopping time τ. Theorem 1 presents a new representation of the asymptotic oscillations of the algorithm. In Section 4, the distribution of the algorithm *cost* is investigated. Using the binary decomposition of the interval $[0, 1]$, the exact expression of the distribution of H_n is established. Proposition 3 is a slight variation of the asymptotic formula given by Janson and Szpankowski (1997) for the distribution of the algorithm *cost* H_n in the biased case.

1.6 Notations

Throughout this paper, $(t_n)_{n\geq 1}$ is a non decreasing random variables sequence such that

- t_1 follows an exponential distribution with parameter 1,
- $(t_{n+1} - t_n)$ is a sequence of *i.i.d.* random variables exponentially distributed with parameter 1.

For $x \geq 0$, let $\mathcal{N}_x$ be the number of t_n in the interval $[0, x]$. It is a r. v. with *Poisson* distribution .

2 Average Cost of The Algorithm

2.1 Algorithm cost

The algorithm *cost* is the number of steps needed to find a *leader*, or equivalently the *height* of the associated tree. Denote by H_n this quantity when the size of the initial group of items is n, then, for $n \geq 2$, this random variable verifies a recurrence relation;

$$H_n \overset{dist.}{=} 1 + H_{1,S_n}\, \mathbf{1}_{\{S_n \neq 0\}} + H_{2,n}\, \mathbf{1}_{\{S_n = 0\}},$$

with the boundary conditions $H_0 = H_1 = 0$, where $(B_i(p))_{1\leq i\leq n}$ are n independent *Bernoulli* variables of parameter p,

$$S_n = \sum_{i=1}^{n} B_i(p),$$

for $(m, n) \in \mathbb{N}^2$, $H_{1,m}$ and $H_{2,n}$ are independent and, for $i = 1, 2$, the variable $H_{i,m}$ has the same distribution as H_m. So, for $n \geq 0$, the recurrence equation for the sequence (H_n) can be rewritten

$$H_n \overset{dist.}{=} 1 + H_{S_n} + H_n\, \mathbf{1}_{(S_n=0)} - \mathbf{1}_{\{n\leq 1\}}. \tag{2}$$

2.2 Poissonization

Consider the *Poisson* model, *i.e.* the size of the initial group of items is random following a *Poisson* process $\mathcal{N}_x$ of intensity 1 on the interval $[0, x]$. The following proposition gives a useful representation of the *Poisson transform* of the average *cost* of the algorithm.

Proposition 1 *For $x > 0$,*

$$\mathbb{E}(H_{\mathcal{N}_x}) = \mathbb{E}\left(\sum_{i=0}^{+\infty} \frac{1}{\pi_i}\, \mathbf{1}_{\{t_1 > x\pi_i\, ;\, t_2 \leq x(\alpha_i+\pi_i)\}}\right),$$

where (A_j, B_j) *is a sequence of i.i.d. realizations of a couple of random variable* (A, B) *with distribution*

$$\mathbb{P}(A = p, B = 0) = p,\ \mathbb{P}(A = q, B = p) = q,$$

$\pi_0 = 1,\ \alpha_0 = 0$ *and, for* $i \geq 1$,

$$\pi_i = \prod_{j=0}^{i-1} A_j,\ \alpha_i = \sum_{j=0}^{i-1} \pi_j\, B_j.$$

Proof: Let h the *Poisson transform* of the average *cost* (see Definition 2). Then, the recurrence equation (2) for the sequence $(H_n)_{n\geq 0}$ becomes

$$h(x) = h(px) + h(qx)\, e^{-px} + 1 - (1 + x)e^{-x}.$$

Following the approach of Mohamed and Robert (2005), direct iteration becomes possible using a probabilistic formulation of the last equation as below

$$h(x) = \mathbb{E}\left(\frac{h(Ax)}{A}\, e^{-Bx}\right) + f(x), \tag{3}$$

where $f(x) = 1 - (1 + x)e^{-x}$ and (A, B) is couple of random variables with distribution

$$\mathbb{P}(A = p, B = 0) = p,\ \mathbb{P}(A = q, B = p) = q.$$

Let the sequence of *i.i.d* realizations $(A_i, B_i)_{i\in\mathbb{N}}$ of the couple of random variables (A, B). We introduce some notations; for $x \geq 0$, $X_0 = x,\ Y_0 = 0$, and for $n \in \mathbb{N}$,

$$X_{n+1} = A_n\, X_n,\ Y_{n+1} = B_n\, X_n.$$

By iterations of equation (3), one gets at the $(n + 1)^{th}$ stage

$$h(x) = \mathbb{E}\left(\frac{h(X_{n+1})}{\prod_{i=0}^{n} A_i}\, e^{-\sum_{i=0}^{n+1} Y_i}\right) + \mathbb{E}\left(\sum_{i=0}^{n} e^{-\sum_{j=0}^{i} Y_j}\, \frac{f(X_i)}{\prod_{j=0}^{i-1} A_j}\right).$$

Since $h'(0) = 0$ and, almost surely, $\lim_{n\to+\infty} X_{n+1} = 0$, then, one obtains

$$h(x) = \mathbb{E}\left(\sum_{i=0}^{+\infty} \frac{1}{\pi_i}\left(1 - (1 + \pi_i)e^{-\pi_i x}\right) e^{-\alpha_i x}\right),$$

where $\pi_0 = 1,\ \alpha_0 = 0$ and, for $i \geq 1$,

$$\pi_i = \prod_{j=0}^{i-1} A_j,\ \alpha_i = \sum_{j=0}^{i-1} \pi_j\, B_j.$$

As the sequences (α_i) and $(\alpha_i + \pi_i)$ are, almost surely, in the interval $[0, 1]$, the function h can be represented as follows

$$h(x) = \mathbb{E}\left(\sum_{i=0}^{+\infty} \frac{1}{\pi_i}\, \mathbf{1}_{\{t_1 > \alpha_i x\,;\, t_2 < (\alpha_i + \pi_i)x\}}\right). \tag{4}$$

The proposition has been proved. □

¿From now on, throughout the paper, we conserve the notations introduced in this proof.

2.3 de-Poissonization

The next step is the probabilistic de-Poissonization of (4) following the method of Robert (2005) to obtain the expression of the average *cost* $\mathbb{E}(H_n)$.

Proposition 2 (Probabilistic representation of the average cost) *For $n \geq 2$,*

$$\mathbb{E}(H_n) = \mathbb{E}\left(\sum_{i=0}^{\tau(U_{1,n},U_{2,n})-1} \frac{1}{\pi_i}\right),$$

where, for $0 < x < y < 1$, $\tau(x,y) = \min(\nu(x); \mu(y))$ with

$$\begin{aligned} \nu(x) &= \inf\{i \geq 1 : \alpha_i > x\}, \\ \mu(y) &= \inf\{i \geq 1 : \alpha_i + \pi_i < y\}, \end{aligned}$$

and $U_{i,n}$ is the ith smallest variables of n independent, uniformly distributed random variables on $[0,1]$ independent of the sequence $(A_j, B_j)_{j\geq 0}$.

Proof: For $x > 0$, by decomposing with respect to the number of points of the Poisson process $(\mathcal{N}_x)$ in the interval $[0,x]$, one gets, for $0 < a < b < 1$,

$$\mathbb{P}(t_1 > ax\,,\, t_2 < bx) = \sum_{n=2}^{+\infty} \mathbb{P}(t_1 > ax\,,\, t_2 < bx | \mathcal{N}_x = n)\mathbb{P}(\mathcal{N}_x = n).$$

For $n \geq 2$, conditionally on the event $\{\mathcal{N}_x = n\}$, the couple of variables (t_1, t_2) has the same distribution as the couple $(xU_{1,n}, xU_{2,n})$ of the two smallest random variables of n uniformly distributed random variables on $[0,x]$. So, we get the identity

$$\mathbb{P}(t_1 > ax,\, t_2 < bx) = \mathbb{E}\left(\sum_{n=2}^{+\infty} \mathbf{1}_{\{U_{1,n}>a,\, U_{2,n}<b\}} \frac{x^n}{n!} e^{-x}\right).$$

Due to the independence of the sequence (A_i, B_i) and (t_1, t_2), and using the Fubini's Theorem, one gets

$$\mathbb{E}(H_{\mathcal{N}_x}) = \sum_{n=2}^{+\infty} \left(\mathbb{E}\left(\sum_{i=0}^{+\infty} \frac{1}{\pi_i} \mathbf{1}_{\{U_{1,n}>\pi_i\,,\, U_{2,n}<(\alpha_i+\pi_i)\}}\right)\right) \frac{x^n}{n!} e^{-x}.$$

The identification of the representation of the *Poisson transform* (see Definition 2) $\mathbb{E}(H_{\mathcal{N}_x})$ and the last identity gives the following formula for $n \geq 2$

$$\mathbb{E}(H_n) = \mathbb{E}\left(\sum_{i=0}^{+\infty} \frac{1}{\pi_i} \mathbf{1}_{\{U_{1,n}>\pi_i\,,\, U_{2,n}<(\alpha_i+\pi_i)\}}\right).$$

Since, almost surely, the sequence $(\alpha_i)_{i\geq 0}$ is increasing to a random variable $\alpha \in [0,1]$ and the sequence $(\alpha_i + \pi_i)_{i\geq 0}$ is decreasing to the same random variable, the following equality holds

$$\{i \geq 0\ : U_{1,n} > \pi_i\,,\, U_{2,n} < \alpha_i + \pi_i\} = [0, \tau(U_{1,n}, U_{2,n}) - 1],$$

where the hitting time τ is defined as above. □

3 Asymptotic Analysis of The Average Cost

3.1 Two random sequences and one hitting time

It is clear that the key of the analysis of the asymptotic behavior of the algorithm is the hitting time τ written on the two random sequences $(\alpha_i)_{i\geq 0}$ and $(\alpha_i+\pi_i)_{i\geq 0}$. Let (γ_i) the sequence of random variables defined by

$$(\gamma_i)_{i\in\mathbb{N}} = \{j \geq 0 \,:\, B_j = p\}.$$

These are the moments of jump of the sequence $(\alpha_i)_{i\geq 0}$ and conversely the instants of stopping for the other one, $(\pi_i+\alpha_i)_{i\geq 0}$. It is clear that these moments can be recursively defined as below: $\gamma_0 = G_0$ and $\gamma_{n+1} = 1+\gamma_n + G_{n+1}$, where $(G_n)_{n\geq 0}$ is a sequence of *i.i.d* r. v. with a geometric distribution $Geo(q)$

$$\mathbb{P}(Geo(q)=k) = q\,p^k.$$

So, it is easy to see that

$$\nu(x) \in \{1+\gamma_i \,:\, i\in\mathbb{N}\},\ \mu(y) \notin \{1+\gamma_i \,:\, i\in\mathbb{N}\}.$$

Using a discussion on the position of the hitting time τ in comparison with the sequence γ, we establish the following lemma which will be proved in the Appendix 5.

Lemma 1

$$\begin{aligned}\mathbb{E}\left(\sum_{i=0}^{\tau(x,y)-1}\frac{1}{\pi_i}\right) &= \lceil \log_p(y)\rceil + \left(\lceil \log_p(\rho(\log_p(y))y)\rceil - \lfloor \log_p(y)\rfloor\right)\mathbf{1}_{\Omega(x,y)} \\ &+ \mathbb{E}\left(\sum_{i=1+\lceil \log_p(\rho(\log_p(y))y)\rceil}^{\tau(x,y)-1}\frac{1}{\pi_i}\mathbf{1}_{\{\gamma_0=\lfloor \log_p(y)\rfloor;\gamma_1=\lceil \log_p(\rho(\log_p(y))y)\rceil\}}\right)\mathbf{1}_{\Omega(x,y)}.\end{aligned}$$

where $\Omega(x,y) = \{(x,y)\in(]0,1[)^2 \,:\, \lceil \log_p(y)\rceil = \lceil \log_p(x)\rceil\}$ *and* ρ *is a periodic function with magnitude* 1 *defined for* $z>0$ *by*

$$\rho(z) = \frac{1-p^{1-\{z\}}}{1-p}\ ,\ \{z\} = z - \lfloor z\rfloor \text{ is the fractional part of } z.$$

3.2 Asymptotic fluctuations phenomena

Theorem 1 (Asymptotic behavior of the average cost) *The average cost* $\mathbb{E}(H_n)$ *admits the following asymptotic formula*

$$\mathbb{E}(H_n) = -\log_p(n) + \mathbb{E}\left(\lceil \log_p(t_2)\rceil\right) + F(\log_p(n)) + \mathcal{R}(n),$$

where F *is a periodic function defined for all* $z>0$ *by*

$$F(z) = \int_0^\infty y(1-p^{1-\{\log_p y - z\}})\left(\lceil \log_p(\frac{1-p^{1-\{\log_p y - z\}}}{1-p}) + \log_p y - z\rceil - \lfloor \log_p y - z\rfloor\right)e^{-y}dy, \tag{5}$$

$\Omega_n = \Omega(U_{1,n}, U_{2,n})$ *and* $\mathcal{R}(n)$ *is a rest discussed in Section* 3.3*, defined by*

$$\mathcal{R}(n) = \mathbb{E}\left(\Big(\sum_{i=1+\lceil \log_p(\rho(\log_p(U_{2,n}))U_{2,n})\rceil}^{\tau(U_{1,n},U_{2,n})-1} \frac{1}{\pi_i} \Big) \mathbf{1}_{\{\gamma_0=\lfloor \log_p(U_{2,n})\rfloor;\gamma_1=\lceil \log_p(\rho(U_{2,n})U_{2,n})\rceil\}}\, \mathbf{1}_{\Omega_n} \right). \quad (6)$$

Proof: Using Lemma 1, one gets

$$\begin{aligned}\mathbb{E}(H_n) &= \mathbb{E}\left(\lceil \log_p(U_{2,n})\rceil\right) + \mathbb{E}\left((\lceil \log_p(\rho(\log_p(U_{2,n}))U_{2,n})\rceil - \lfloor \log_p(U_{2,n})\rfloor)\mathbf{1}_{\Omega_n}\right) \\ &+ \mathbb{E}\left(\Big(\sum_{i=1+\lceil \log_p(\rho(\log_p(y))y)\rceil}^{\tau(U_{1,n},U_{2,n})-1} \frac{1}{\pi_i} \Big) \mathbf{1}_{\{\gamma_0=\lfloor \log_p(U_{2,n})\rfloor;\gamma_1=\lceil \log_p(\rho(U_{2,n})U_{2,n})\rceil\}}\, \mathbf{1}_{\Omega_n} \right).\end{aligned}$$

The only not neglect terms are

$$\mathcal{T}_1(n) = \mathbb{E}\left(\lceil \log_p(U_{2,n})\rceil\right) \text{ and } \mathcal{T}_2(n) = \mathbb{E}\left((\lceil \log_p(\rho(\log_p(U_{2,n}))U_{2,n})\rceil - \lfloor \log_p(U_{2,n})\rfloor)\mathbf{1}_{\Omega_n}\right).$$

As n goes to infinity, $nU_{2,n}$ converges in distribution to a random variable t_2 which is a sum of two *i.i.d.* exponential random variables with parameter 1.Then, the first term satisfies

$$\mathcal{T}_1(n) = \mathbb{E}(\lceil \log_p(t_2) - \log_p(n)\rceil) + O(\frac{1}{n}).$$

Let $\mathcal{D}$, function of $-\log_p(n)$, the difference

$$\mathcal{D}(-\log_p(n)) = \mathbb{E}(\lceil \log_p(t_2) - \log_p(n)\rceil) - \big(\mathbb{E}(\lceil \log_p(t_2)\rceil) - \log_p(n)\big)$$

It is easy to check that $\mathcal{D}(z) = \mathcal{D}(\{z\}) - \lfloor z\rfloor$, then $\lim_{n\to+\infty} n\,\mathcal{D}(-\log_p n) = \lim_{z\to+\infty} p^{-z}\,\mathcal{D}(z) = 0$, and one gets

$$\mathcal{T}_1(n) = -\log_p(n) + \mathbb{E}(\lceil \log_p(t_2)\rceil) + O(\frac{1}{n}).$$

The last term $\mathcal{T}_2(n)$ is asymptotically equivalent to $F(\log_p(n))$ where F is defined by 5. In fact

$$|F(\log_p(n)) - \mathcal{T}_2(n)| \le \int_0^n \left|(1-\frac{y}{n})^{n-2} - e^{-y}\right| dy + \int_n^\infty \log_p(\rho(\log_p(y/n)))\, y\, e^{-y} dy + \frac{1}{n}F(\log_p(n)) + 2e^{-n}$$

Observe that

$$\int_n^\infty \log_p(\rho(\log_p(y/n)))\, y\, e^{-y} dy = n^2 \int_1^\infty \log_p(\rho(\log_p y))y\, e^{-ny} dy.$$

By decomposition on the sequence of intervals $\big([p^{k+1}, p^k]\big)$, the last integral is dominated by a geometric sum and the following inequality holds for $n > 2$

$$\int_1^\infty \log_p(\rho(\log_p(y)))\, y\, e^{-ny} dy \le \frac{p^{n-2}}{1-p}.$$

Then,

$$F(\log_p(n)) - \mathbb{E}\left((\lceil \log_p(\rho(\log_p(U_{2,n}))U_{2,n})\rceil - \lfloor \log_p(U_{2,n})\rfloor)\mathbf{1}_{\Omega_n}\right) = O(\frac{1}{n}).$$

This ends the proof. □

3.3 Estimation of the rest

The final step is to estimate the rest $\mathcal{R}(n)$ defined by (6). For $x, y \in [0,1]$, $K > k > 0$

$$\mathbb{E}\left(\sum_{i=K}^{\tau(x,y)-1} \frac{1}{\pi_i}\, \mathbf{1}_{\{\gamma_0=k;\gamma_1=K\}}\right) \leq (1-\delta)^K \sqrt{\mathbb{E}\left((\frac{1}{\delta^2})^{\tau(x,y)}\right)},$$

where $\delta = \min(p,q)$. The following result is admitted.

Conjecture 1 *The hitting time τ satisfies*

$$\sup_{x\in[0,1]} \mathbb{E}\left((\frac{1}{\delta^2})^{\tau(x,x)}\right) < \infty.$$

Remark 1 *Conjecture 1 is an intuitive restriction on the exponential moment of the hitting time τ. It is supported by some simulations (Fig.2,3) of $x :\longrightarrow \mathbb{E}\left((\frac{1}{\delta^2})^{\tau(x,x)}\right)$ using Monte-Carlo techniques. Observe that, for the unbiased case (Fig.2), the maximum corresponds to numerical values of x around 0.5 which is, on average, the limit α of the two random sequences (α_i) and $(\alpha_i + \pi_i)$. This maximum is of order of 10^{14}, which is reasonable since it implies that*

$$\mathbb{E}(\tau) \leq 14\ \log_4(10) \approx 23.25$$

For the biased one (Fig.3), since $\delta = 0.2$, a maximum of the order of 10^{80} is acceptable; $\mathbb{E}(\tau) \leq 57.22$.

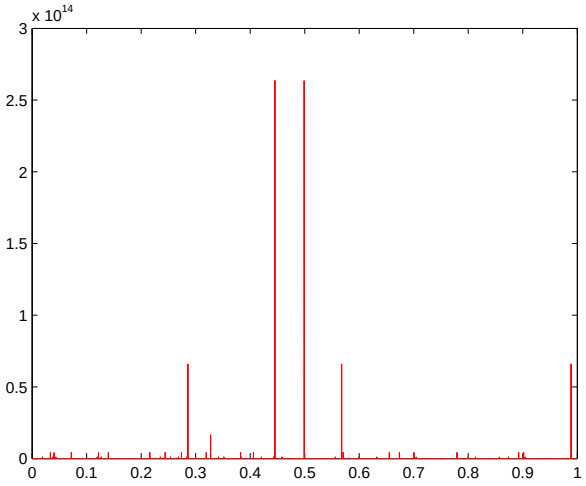
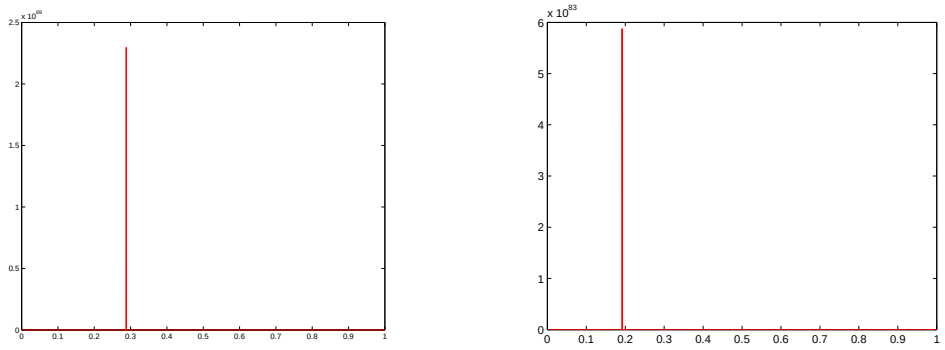


Fig. 2: Unbiased case: simulations of $x :\longrightarrow \mathbb{E}\left(4^{\tau(x,x)}\right)$.



(a) $p = 0.2,\ \delta = p$ (b) $p = 0.8,\ \delta = 1 - p$

Fig. 3: Biased case: simulations of $x :\longrightarrow \mathbb{E}\left(\frac{1}{\delta^2}^{\tau(x,x)}\right)$.

Since, for $0 \leq x < y \leq 1$, $\tau(x,y) \leq \max(\tau(x,x),\ \tau(y,y))$, then, using Conjecture 1, we obtain

$$\mathcal{R}(n) \leq C\,\mathbb{E}\left((1-\delta)^{\lceil \log_p(\rho(U_{2,n})U_{2,n})\rceil}\right),$$

where $C = \sup_{x\in[0,1]} \sqrt{\mathbb{E}\left((1/\delta^2)^{\tau(x,x)}\right)}$. Using the same method as for the function F, one gets

$$\mathbb{E}\left((1-\delta)^{\lceil \log_p(\rho(U_{2,n})U_{2,n})\rceil}\right) \leq \mathbb{E}\left((1-\delta)^{\lceil \log_p(U_{2,n})\rceil}\right) \sim \left(\frac{1}{n}\right)^{\log_p(1-\delta)}.$$

This gives

$$\mathcal{R}(n) = O(\frac{1}{n^{\log_p(1-\delta)}}).$$

Conclusion

$$\mathbb{E}(H_n) = -\log_p(n) + \mathbb{E}\left(\lfloor \log_p(t_2)\rfloor\right) + F(\log_p(n)) + O(\frac{1}{n^{\log_p(1-\delta)}}).$$

4 Algorithm Cost Distribution

It is more appropriate to use these notations $p_0 = p,\ p_1 = q$, to define recursively the sequence of intervals (I_k^n) associated to the binary decomposition of the interval $[0,1]$ in the base $(p_0,\ p_1)$

$$\left\{\begin{array}{ll} I_0^0 & = [0,1] \\ I_k^{n+1} & = \left(I_{k-1}^{n+1}\right)_+ + p_{k-2\lfloor k/2\rfloor}\, I_{\lfloor k/2\rfloor}^n, \end{array}\right.$$

where $(I)_+$ denotes the right extremity of the interval I. Let $|I|$ the length of the interval I, then

$$(I_k^n)_+ = \sum_{i=0}^{k} |I_i^n|.$$

Let $n \in \mathbb{N}$ and $0 \leq k \leq 2^{n+1} - 1$. Consider the binary decomposition of k at the stage n

$$k = a_0 + a_1 2 + \ldots + a_n 2^n, \text{ for } 0 \leq i \leq n, \ a_i \in \{0, 1\}.$$

Then, the length of the interval I_k^{n+1} is

$$|I_k^{n+1}| = \prod_{i=0}^{n} p_{a_i}.$$

For $k \in \mathbb{N}$, $x > 0$, one gets the following identity

$$\{H_{\mathcal{N}_x} > k\} = \{\exists\, 0 \leq i < 2^k \,:\, \mathcal{N}(xI_0^k) = \ldots = \mathcal{N}(xI_{i-1}^k) = 0\,,\, \mathcal{N}(xI_i^k) \geq 2\}.$$

So

$$\mathbb{P}(H_{\mathcal{N}_x} \leq k) = e^{-x} + x \sum_{i=0}^{2^k-1} |I_i^k| e^{-\left(I_i^k\right)_+}. \tag{7}$$

Let us define the sequence of probability measures (μ_k) by

$$\mu_k(t) = \sum_{i=0}^{2^k-1} |I_i^k|\, \delta_{\left(I_i^k\right)_+}(t).$$

Then, equation (7) can be rewritten as

$$\mathbb{P}(H_{\mathcal{N}_x} \leq k) = e^{-x} + x \int_0^1 e^{-xt}\, d\mu_k(t). \tag{8}$$

Using a probabilistic de-Poissonization of equation (8) as done for Proposition 2, we obtain the exact distribution of H_n.

Proposition 3 *For $n \geq 2$,*

$$\mathbb{P}(H_n \leq k) = n \int_0^1 (1-t)^{n-1}\, d\mu_k(t),$$

where the probability measure μ_k is described as above.

Using this identity

$$1 - n(1-t)^{n-1} = 1 - nt\,(1-t)^{n-1} - n(1-t)^n,$$

the following result is immediate.

Corollary 1 *For $k \in \mathbb{N}$,*

$$\mathbb{P}(H_n > k) \sim \int_0^1 \mathbb{P}(U_{2,n} < t)\, d\mu_k(t) \text{ , as } n \text{ goes to infinity.}$$

where $U_{2,n}$ is the second smallest random variable of n uniformly distributed random variables on $[0.1]$

5 Appendix

We present the proof of Lemma 1. Recall the sequence of random variables (γ_i) defined by

$$(\gamma_i)_{i\in\mathbb{N}} = \{j \geq 0 \,:\, B_j = p\}.$$

Proof of Lemma 1**:** First, note that

$$\begin{aligned}(\nu(x) \geq 2+\gamma_0) &\Leftrightarrow (\gamma_0 \geq \lfloor \log_p(x)\rfloor)\\ (\mu(y) \leq \gamma_0) &\Leftrightarrow (\gamma_0 \geq \lceil \log_p(y)\rceil).\end{aligned}$$

Denote by Ω_0 the following set

$$\Omega_0 = \Omega(x,y) := \{(x,y) \in (]0,1[)^2 \,:\, \lceil \log_p(y)\rceil = \lceil \log_p(x)\rceil\}.$$

By decomposing the function Φ with respect to Ω_0, one gets this formula

$$\begin{aligned}\mathbb{E}\left(\sum_{i=0}^{\tau(x,y)-1}\frac{1}{\pi_i}\right) &= \mathbb{E}\left(\sum_{i=0}^{\gamma_0}\frac{1}{p^i}\mathbf{1}_{\{\gamma_0<\lfloor \log_p(y)\rfloor\}}\right) + \mathbb{P}\left(\gamma_0 = \lfloor \log_p(y)\rfloor\right)\sum_{i=0}^{\lfloor \log_p(y)\rfloor}\frac{1}{p^i} + \mathbb{E}\left(\sum_{i=0}^{\mu(y)-1}\frac{1}{p^i}\mathbf{1}_{\{\gamma_0\geq\lceil \log_p(y)\rceil\}}\right)\\ &+ \mathbb{E}\left(\Big(\sum_{i=\lceil \log_p(y)\rceil}^{\tau(x,y)-1}\frac{1}{\pi^i}\Big)\mathbf{1}_{\{\gamma_0=\lfloor \log_p(y)\rfloor\}}\right)\mathbf{1}_{\Omega_0}.\end{aligned}$$

Since

$$\mu(y)|(\gamma_0 \geq \lceil \log_p(y)\rceil) = \inf\{i\geq 1, p^i < y\} = \lceil \log_p(y)\rceil,$$

then, by simple calculations, one gets

$$\mathbb{E}\left(\sum_{i=0}^{\tau(x,y)-1}\frac{1}{\pi_i}\right) = \lceil \log_p(y)\rceil + \mathbb{E}\left(\Big(\sum_{i=\lceil \log_p(y)\rceil}^{\tau(x,y)-1}\frac{1}{\pi^i}\Big)\mathbf{1}_{\{\gamma_0=\lfloor \log_p(y)\rfloor\}}\right)\mathbf{1}_{\Omega_0}.$$

A second discussion on γ_1 implies that, on the set $(\gamma_0 = \lfloor log_p(y)\rfloor, \Omega_0)$,

$$\begin{aligned}(\nu(x) \geq 2+\gamma_1) &\Leftrightarrow (\gamma_1 \geq \lceil \log_p(\rho(\log_p(x))x)\rceil)\\ (\mu(y) \leq \gamma_1) &\Leftrightarrow (\gamma_1 \geq 1+\lceil \log_p(\rho(\log_p(y))y)\rceil),\end{aligned}$$

where ρ is a periodic function with magnitude 1 defined by $\rho(z) = (1-p^{1-\{z\}})/(1-p)$. Moreover, ρ is decreasing on $[0,1[$, so on the set Ω_0,

$$\rho(\log_p(x))x < \rho(\log_p(y))y.$$

Let $\Omega_1 = \Omega(\rho(\log_p(x))x, \rho(\log_p(y))y)$. Then

$$\begin{aligned}\mathbb{E}\left(\sum_{i=0}^{\tau(x,y)-1}\frac{1}{\pi_i}\right) &= \lceil \log_p(y)\rceil + \left(\lceil \log_p(\rho(\log_p(y))y)\rceil - \lfloor \log_p(y)\rfloor\right)\mathbf{1}_{\Omega(x,y)}\\ &+ \mathbb{E}\left(\sum_{i=1+\lceil \log_p(\rho(\log_p(y))y)\rceil}^{\tau(x,y)-1}\frac{1}{\pi_i}\,\mathbf{1}_{\{\gamma_0=\lfloor \log_p(y)\rfloor;\gamma_1=\lceil \log_p(\rho(\log_p(y))y)\rceil\}}\right)\mathbf{1}_{\Omega(x,y)}.\end{aligned}$$

This ends the proof. □

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