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Sinai's walk : a statistical aspect (preliminary version)

Pierre Andreatti *

December 8, 2006

Abstract: We consider Sinai's random walk in random environment. We prove that the logarithm of the local time is a good estimator of the random potential associated to the random environment. We give a constructive method allowing us to build the random environment from a single trajectory of the random walk.

1 Introduction and results

In this paper we are interested in Sinai's walk i.e a one dimensional random walk in random environment with three conditions on the random environment: two necessary hypothesis to get a recurrent process (see [Solomon(1975)]) which is not a simple random walk and an hypothesis of regularity which allows us to have a good control on the fluctuations of the random environment.

The asymptotic behavior of such walk has been understood by [Sinai(1982)] : this walk is sub-diffusive and at an instant n it is localized in the neighborhood of a well defined point of the lattice. It is well known, see (Zeitouni [2001] for a survey) that this behavior is strongly dependent of the random environment or, equivalently, by the associated random potential defined Section 1.2.

The question we solve here is the following: given a single trajectory of a random walk $(X_k, 1 \leq k \leq n)$ where n is fixed, can we estimate the trajectory of the random potential where the walk lives ? Let us remark that the law of this potential is unknown as-well. In their paper, [Adelman and Enriquez(2004)] answer this question in the parametrical case when the law of the random environment is defined by two parameters.

On the other hand, our approach is a non-parametrical approach based on good properties of the local time of the random walk. We are able to reconstruct the random potential in a significant interval where the walk spends most of its time. The key point of this paper is that if we impose to the local time to be large enough but negligible comparing to the maximum of the local time then this will directly implies conditions on the random potential. Notice that, this aspect of looking the random

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environment from the point of view of the walk have already been studied for a different purpose than our in for example [Kesten(1977)]. Our proof is based on the results of [Andreoletti(2005)], in particular in a weak law of large number for the local time on the point of localization of the walk.

The largest part of this paper is devoted to the proof of a theoretical result (Theorem 1.8) but as this paper has been motivated by numerical simulations we also present some of them at the end of the document. We give the main steps of the algorithm we use to rebuilt the random potential only by considering a trajectory of the walk. Let us comment one of these simulations:

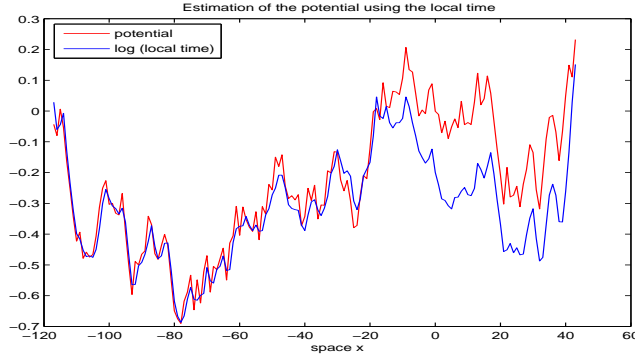


Figure 1: The logarithm of the local time (in blue) and the random potential (in red)

In blue we have represented the logarithm of the local time and in red the potential associated to the random environment. First, remark that we observe a good approximation on a large neighborhood of the bottom of the valley around the coordinate -80. Outside this neighborhood and especially after the coordinate -20, the approximation is not precise at all. We will explain this phenomena by the fact that after the walk has reached the bottom of the valley, the walk will not return frequently to the points with coordinate larger than -20, so we lose information for this part of the lattice.

Our method of estimation give us two crucial information: a confidence interval for the differences of potential in sup-norm, on an observable set of sites “sufficiently” visited by the walk and a localization result for the bottom of the valley linked with the hitting time of the maximum of the local times. First we need to define the process:

1.1 Definition of Sinai’s walk

Let $\alpha = (\alpha_i, i \in \mathbb{Z})$ be a sequence of i.i.d. random variables taking values in $(0, 1)$ defined on the probability space $(\Omega_1, \mathcal{F}_1, Q)$, this sequence will be called random environment. A random walk in random environment (denoted R.W.R.E.) $(X_n, n \in \mathbb{N})$ is a sequence of random variable taking value in \mathbb{Z} , defined on $(\Omega, \mathcal{F}, \mathbb{P})$ such that

- for every fixed environment α , $(X_n, n \in \mathbb{N})$ is a Markov chain with the following transition probabilities, for all $n \geq 1$ and $i \in \mathbb{Z}$

$$\begin{aligned} \mathbb{P}^\alpha [X_n = i + 1 | X_{n-1} = i] &= \alpha_i, \\ \mathbb{P}^\alpha [X_n = i - 1 | X_{n-1} = i] &= 1 - \alpha_i \equiv \beta_i. \end{aligned} \tag{1.1}$$

We denote $(\Omega_2, \mathcal{F}_2, \mathbb{P}^\alpha)$ the probability space associated to this Markov chain.

- $\Omega = \Omega_1 \times \Omega_2$, $\forall A_1 \in \mathcal{F}_1$ and $\forall A_2 \in \mathcal{F}_2$, $\mathbb{P}[A_1 \times A_2] = \int_{A_1} Q(dw_1) \int_{A_2} \mathbb{P}^{\alpha(w_1)}(dw_2)$.

The probability measure $\mathbb{P}^\alpha [\cdot | X_0 = a]$ will be denoted $\mathbb{P}_a^\alpha [\cdot]$, the expectation associated to \mathbb{P}_a^α : \mathbb{E}_a^α , and the expectation associated to Q : \mathbb{E}_Q .

Now we introduce the hypothesis we will use in all this work. The two following hypothesis are the necessary hypothesis

$$\mathbb{E}_Q \left[\log \frac{1 - \alpha_0}{\alpha_0} \right] = 0, \quad (1.2)$$

$$\text{Var}_Q \left[\log \frac{1 - \alpha_0}{\alpha_0} \right] \equiv \sigma^2 > 0. \quad (1.3)$$

[Solomon(1975)] shows that under 1.2 the process $(X_n, n \in \mathbb{N})$ is \mathbb{P} almost surely recurrent and 1.3 implies that the model is not reduced to the simple random walk. In addition to 1.2 and 1.3 we will consider the following hypothesis of regularity, there exists $0 < \eta_0 < 1/2$ such that

$$\sup \{x, Q[\alpha_0 \geq x] = 1\} = \sup \{x, Q[\alpha_0 \leq 1 - x] = 1\} \geq \eta_0. \quad (1.4)$$

We call *Sinai's random walk* the random walk in random environment previously defined with the three hypothesis 1.2, 1.3 and 1.4.

Let us define the local time \mathcal{L} , at k ($k \in \mathbb{Z}$) within the interval of time $[1, T]$ ($T \in \mathbb{N}^*$) of $(X_n, n \in \mathbb{N})$

$$\mathcal{L}(k, T) \equiv \sum_{i=1}^T \mathbb{I}_{\{X_i=k\}}. \quad (1.5)$$

\mathbb{I} is the indicator function (k and T can be deterministic or random variables). Let $V \subset \mathbb{Z}$, we denote

$$\mathcal{L}(V, T) \equiv \sum_{j \in V} \mathcal{L}(j, T) = \sum_{i=1}^T \sum_{j \in V} \mathbb{I}_{\{X_i=j\}}. \quad (1.6)$$

To end, we define the following random variables

$$\mathcal{L}^*(n) = \max_{k \in \mathbb{Z}} (\mathcal{L}(k, n)), \quad \mathbb{F}_n = \{k \in \mathbb{Z}, \mathcal{L}(k, n) = \mathcal{L}^*(n)\}, \quad (1.7)$$

$$k^* = \inf\{|k|, k \in \mathbb{F}_n\} \quad (1.8)$$

$\mathcal{L}^*(n)$ is the maximum of the local times (for a given instant n), \mathbb{F}_n is the set of all the favourite sites and k^* the smallest favorite site.

1.2 The random potential and the valleys

From the random environment we define what we will call random potential,

Let

$$\epsilon_i \equiv \log \frac{1 - \alpha_i}{\alpha_i}, \quad i \in \mathbb{Z}, \quad (1.9)$$

define :

Definition 1.1. The random potential $(S_m, m \in \mathbb{Z})$ associated to the random environment α is defined in the following way: for all k and j , if $k > j$

$$S_k - S_j = \begin{cases} \sum_{j+1 \leq i \leq k} \epsilon_i, & k \neq 0, \\ -\sum_{j \leq i \leq -1} \epsilon_i, & k = 0, \\ S_0 = 0, \end{cases}$$

and symmetrically if $k < j$.

Remark 1.2. using Definition 1.1 we have :

$$S_k = \begin{cases} \sum_{1 \leq i \leq k} \epsilon_i, & k = 1, 2, \dots, \\ \sum_{k \leq i \leq -1} \epsilon_i, & k = -1, -2, \dots, \end{cases} \quad (1.10)$$

however, if we use 1.10 for the definition of (S_k, k) , ϵ_0 does not appear in this definition and moreover it is not clear, when $j < 0 < k$, what the difference $S_k - S_j$ means (see figure 2).

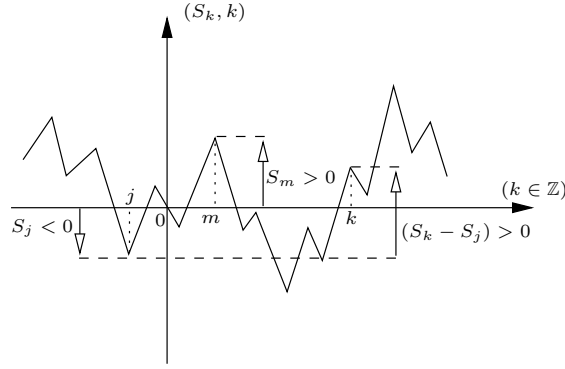


Figure 2: Trajectory of the random potential

Definition 1.3. We will say that the triplet $\{M', m, M''\}$ is a *valley* if

$$S_{M'} = \max_{M' \leq t \leq m} S_t, \quad (1.11)$$

$$S_{M''} = \max_{m \leq t \leq M''} S_t, \quad (1.12)$$

$$S_m = \min_{M' \leq t \leq M''} S_t. \quad (1.13)$$

If m is not unique we choose the one with the smallest absolute value.

Definition 1.4. We will call *depth of the valley* $\{M', m, M''\}$ and we will denote it $d([M', M''])$ the quantity

$$\min(S_{M'} - S_m, S_{M''} - S_m). \quad (1.14)$$

Now we define the operation of *refinement*

Definition 1.5. Let $\{M', m, M''\}$ be a valley and let M_1 and m_1 be such that $m \leq M_1 < m_1 \leq M''$ and

$$S_{M_1} - S_{m_1} = \max_{m \leq t' \leq t'' \leq M''} (S_{t'} - S_{t''}). \quad (1.15)$$

We say that the couple (m_1, M_1) is obtained by a *right refinement* of $\{M', m, M''\}$. If the couple (m_1, M_1) is not unique, we will take the one such that m_1 and M_1 have the smallest absolute value. In a similar way we define the *left refinement* operation.

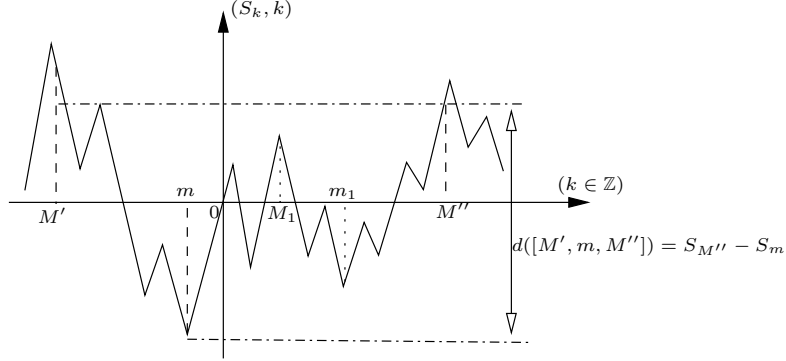


Figure 3: Depth of a valley and refinement operation

We denote $\log_2 = \log \log$, in all this section we will suppose that n is large enough such that $\log_2 n$ is positive.

Definition 1.6. Let $n > 3$, $\gamma > 0$, and $\Gamma_n \equiv \log n + \gamma \log_2 n$, we say that a valley $\{M', m, M''\}$ contains 0 and is of depth larger than Γ_n if and only if

1. $0 \in [M', M'']$,
2. $d([M', M'']) \geq \Gamma_n$,
3. if $m < 0$, $S_{M''} - \max_{m \leq t \leq 0} (S_t) \geq \gamma \log_2 n$,
if $m > 0$, $S_{M'} - \max_{0 \leq t \leq m} (S_t) \geq \gamma \log_2 n$.

The basic valley $\{M_n', m_n, M_n\}$

We recall the notion of *basic valley* introduced by Sinai and denoted here $\{M_n', m_n, M_n\}$. The definition we give is inspired by the work of [Kesten(1986)]. First let $\{M', m_n, M''\}$ be the smallest valley that contains 0 and of depth larger than Γ_n . Here smallest means that if we construct, with the operation of refinement, other valleys in $\{M', m_n, M''\}$ such valleys will not satisfy one of the properties of Definition 1.6. M_n' and M_n are defined from m_n in the following way: if $m_n > 0$

$$M_n' = \sup \left\{ l \in \mathbb{Z}_-, l < m_n, S_l - S_{m_n} \geq \Gamma_n, S_l - \max_{0 \leq k \leq m_n} S_k \geq \gamma \log_2 n \right\}, \quad (1.16)$$

$$M_n = \inf \{ l \in \mathbb{Z}_+, l > m_n, S_l - S_{m_n} \geq \Gamma_n \}. \quad (1.17)$$

if $m_n < 0$

$$M_n' = \sup \{l \in \mathbb{Z}_-, l < m_n, S_l - S_{m_n} \geq \Gamma_n\}, \quad (1.18)$$

$$M_n = \inf \left\{ l \in \mathbb{Z}_+, l > m_n, S_l - S_{m_n} \geq \Gamma_n, S_l - \max_{m_n \leq k \leq 0} S_k \geq \gamma \log_2 n \right\}. \quad (1.19)$$

if $m_n = 0$

$$M_n' = \sup \{l \in \mathbb{Z}_-, l < 0, S_l - S_{m_n} \geq \Gamma_n\}, \quad (1.20)$$

$$M_n = \inf \{l \in \mathbb{Z}_+, l > 0, S_l - S_{m_n} \geq \Gamma_n\}. \quad (1.21)$$

$\{M_n', m_n, M_n\}$ exists with a Q probability as close to one as we need. In fact it is not difficult to prove the following lemma

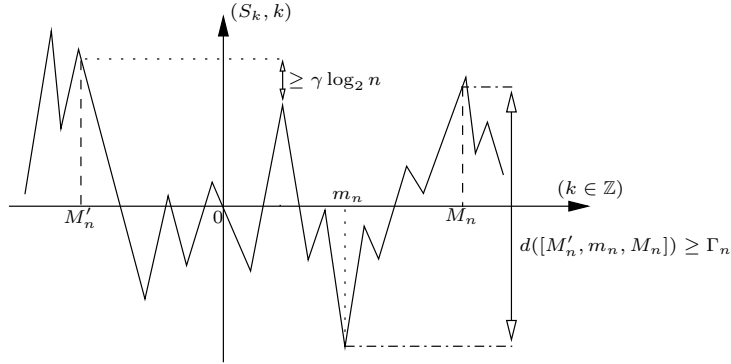


Figure 4: Basic valley, case $m_n > 0$

Lemma 1.7. *There exists $c > 0$ such that if 1.2, 1.3 and 1.4 hold, for all $\gamma > 0$ and n we have*

$$Q [\{M_n', m_n, M_n\} \neq \emptyset] = 1 - \frac{c\gamma \log_2 n}{\log n}. \quad (1.22)$$

Proof.

One can find the proof of this Lemma in Section 5.2 of [Andreoletti(2006)]. ■

1.3 Main results

We start with some definitions that will be used all along this work. Let $x \in \mathbb{Z}$, define

$$T_x = \begin{cases} \inf \{k \in \mathbb{N}^*, X_k = x\} \\ +\infty, \text{ if such } k \text{ does not exist.} \end{cases} \quad (1.23)$$

Let $n > 1$, $k \in \mathbb{Z}$, and $c_0 > 0$, define:

$$S_{k,m_n}^n = 1 - \frac{1}{\log n} (S_k - S_{m_n}), \quad (1.24)$$

$$\hat{S}_k^n = \frac{\log(\mathcal{L}(k, n))}{\log n}, \quad (1.25)$$

$$u_n = \frac{c_0 \log_3 n}{\log n}. \quad (1.26)$$

S_{k,m_n}^n is the function of the potential we want to estimate, \hat{S}_k^n is the estimator and u_n is an error function.

Now let us define the following random sub-set of \mathbb{Z} , recall that $\gamma > 0$:

$$\mathbb{L}_n^\gamma = \left\{ l \in \mathbb{Z}, \sum_{j=T_k^*}^n \mathbb{I}_{X_j=l} \geq ((\log n)^\gamma) \vee (\mathcal{L}(l, T_k^*)) \right\}, \quad (1.27)$$

where $a \vee b = \max(a, b)$. This set \mathbb{L}_n^γ is fundamental for our result, we notice that it depends only on the trajectory of the walk and more especially of its local time. In fact \mathbb{L}_n^γ is the set of points for which we are able to give an estimator of the the random potential. We will see that this set is large and contains a great amount of the points visited by the walk (see Proposition 1.10). Recall that T_k^* is the first time the walk hit the smallest point in absolute value where it will spend the largest amount of time. In words, $l \in \mathbb{L}_n^\gamma$, if and only if: 1) The local time of the random walker in l after the instant T_k^* is large enough (larger than $(\log n)^\gamma$), and 2) The walk have spent more time in l after T_k^* than before this instant.

Our main result is the following:

Theorem 1.8. *Assume 1.2, 1.3 and 1.4 hold, there exists three constants c_0, c_1 and c_2 such that for all $\gamma > 6$, there exists n_0 such that for all $n > n_0$ there exists $G_n \subset \Omega_1$ with $Q[G_n] \geq 1 - \phi_1(n)$ and*

$$\inf_{\alpha \in G_n} \mathbb{P}^\alpha \left[\bigcap_{k \in \mathbb{L}_n^\gamma} \left\{ |\hat{S}_k^n - S_{k,m_n}^n| < u_n \right\} \right] \geq 1 - \phi_2(n). \quad (1.28)$$

where

$$\phi_1(n) = \frac{c_1 \gamma \log_2 n}{\log n}, \quad (1.29)$$

$$\phi_2(n) = \frac{c_2}{(\log n)^{\gamma/2}}. \quad (1.30)$$

The fact that our result depends on m_n seems to be restrictive, we would like to know where is the bottom of the valley only by considering the local time of the walk, so we also prove the following fact :

Proposition 1.9. *Assume 1.2, 1.3 and 1.4 hold, there exists a constant $c_3 > 0$ such that for all $\gamma > 6$, there exists n_0 such that for all $n > n_0$ there exists $G_n \subset \Omega_1$ with $Q[G_n] \geq 1 - \phi_1(n)$ and*

$$\inf_{\alpha \in G_n} \mathbb{P}_0^\alpha \left[\max_{x \in \mathbb{F}_n} |m_n - x| \leq (\log_2 n)^2 \right] \geq 1 - \phi_3(n), \quad (1.31)$$

$$\inf_{\alpha \in G_n} \mathbb{P}_0^\alpha \left[|T_{m_n} - T_{k^*}| \leq (\log n)^3 \right] \geq 1 - \phi_3(n), \quad (1.32)$$

where $\phi_3(n) = c_3/(\log n)^{\gamma-6}$.

Notice that the distance between m_n (coordinate of the point visited by the walk where the minimum of the potential is reached) and a favorite site is negligible comparing to a typical fluctuation of the walk (of order $(\log n)^2$). Thanks to Proposition 1.9 we can replace 1.28 in Theorem 1.8 by

$$\inf_{\alpha \in G_n} \mathbb{P}^\alpha \left[\bigcap_{k \in \mathbb{L}_n^\gamma} \left\{ |\hat{S}_k^n - S_{k,k^*}^n| < u_n \right\} \right] \geq 1 - \phi_2(n). \quad (1.33)$$

Now let us give a result giving the main properties of \mathbb{L}_n^γ .

Proposition 1.10. *Assume 1.2, 1.3 and 1.4 hold,*

$$\inf_{\alpha \in G_n} \mathbb{P}_0^\alpha [\mathcal{L}(\mathbb{L}_n^\gamma, n) = n(1 - o(1))] \geq 1 - \phi_2(n), \quad (1.34)$$

$$\inf_{\alpha \in G_n} \mathbb{P}_0^\alpha [\mathbb{L}_n^\gamma \text{ is connex}] \geq 1 - \phi_2(n), \quad (1.35)$$

$$\inf_{\alpha \in G_n} \mathbb{P}_0^\alpha [|\mathbb{L}_n^\gamma| \geq (\log n)^2] \geq 1 - \phi_2(n). \quad (1.36)$$

Remark 1.11. ...

Remark 1.12. About the variance of the estimator.

Theorem 1.8 is known to be the quenched result that means for a fixed environment α , a simple consequence (see Remark 2.4) is the following annealed result :

Corollary 1.13. *Assume 1.2, 1.3 and 1.4 hold, there exists three constants c_0, c_1 and c_2 such that for all $\gamma > 6$, there exists n_0 such that for all $n > n_0$*

$$\mathbb{P} \left[\bigcap_{k \in \mathbb{L}_n^\gamma} \left\{ \left| \hat{S}_k^k - S_{k,k^*}^n \right| < u_n \right\} \right] \geq 1 - \phi(n), \quad (1.37)$$

where $\phi(n) = \phi_1(n) + \phi_2(n)$.

This paper is organized as follows. In Section 2 we give the proof of Theorems 1.8 (we easily get the corollary from Remark 2.4), we have shared this proof into two parts, the first one deals with the random environment and the other one with the random walk itself. In section 3 we give the sketch the proofs of Propositions 1.9 and 1.10. In Section 4 we present an algorithm to rebuilt the random potential from a trajectory of the walk and some numerical simulations. In the appendix we recall a basic fact for birth and death processes.

2 Proof of Theorem 1.8

The proof of a result with a random environment involves both arguments and properties for the random environment and arguments for the random walk itself. I will start to give the properties I need for the random environment. Then we will use it to get the result for the walk.

2.1 Properties needed for the random environment

2.1.1 Construction of $(G_n, n \in \mathbb{N})$

Let k and l be in \mathbb{Z} , define

$$E_k^\alpha(l) = \mathbb{E}_k^\alpha [\mathcal{L}(l, T_k)] \quad (2.1)$$

in the same way, let $A \subset \mathbb{Z}$, define

$$E_k^\alpha(A) = \sum_{l \in A} \mathbb{E}_k^\alpha [\mathcal{L}(l, T_k)]. \quad (2.2)$$

Definition 2.1. Let $d_0 > 0$, $d_1 > 0$, and $\omega \in \Omega_1$, we will say that $\alpha \equiv \alpha(\omega)$ is a *good environment* if there exists n_0 such that for all $n \geq n_0$ the sequence $(\alpha_i, i \in \mathbb{Z}) = (\alpha_i(\omega), i \in \mathbb{Z})$ satisfies the properties 2.3 to 2.5

$$\bullet \{M_n', m_n, M_n\} \neq \emptyset, \quad (2.3)$$

$$\bullet M_n' \geq -d_0(\sigma^{-1} \log_2 n \log n)^2, \quad M_n \leq d_0(\sigma^{-1} \log_2 n \log n)^2, \quad (2.4)$$

$$\bullet E_{m_n}^\alpha(W_n) \leq d_1(\log_2 n)^2, \quad (2.5)$$

where $W_n = \{M_n', M_n' + 1, \dots, m_n, \dots, M_n\}$.

Remark 2.2. We will see in Section 2 below that we have used some results of [Andreoletti(2006)]. Considering this, we need extra properties about the random environment in addition to the three mentioned above, but as we don't need them for our computations we do not make them appear.

Define the *set of good environments*

$$G_n \equiv G_n(d_0, d_1) = \{\omega \in \Omega_1, \alpha(\omega) \text{ is a good environment}\}. \quad (2.6)$$

G_n depends on d_0 , d_1 and n , however we only make explicit the n dependence.

Proposition 2.3. *There exists two constants $d_0 > 0$ and $d_1 > 0$ such that if 1.2, 1.3 and 1.4 hold, there exists n_0 such that for $n > n_0$*

$$Q[G_n] \geq 1 - \phi_1(n), \quad (2.7)$$

where $\phi_1(n)$ is given by 1.29.

Proof.

We can find the proof for the first three properties 2.3-2.5 in [Andreoletti(2006)], see Definition 4.1 and Proposition 4.2. ■

To end the section we would like to make the following elementary remark on the decomposition of \mathbb{P} :

Remark 2.4. Let $\mathcal{C}_n \in \sigma(X_i, i \leq n)$ and $G_n \subset \Omega_1$, we have :

$$\mathbb{P}[\mathcal{C}_n] \equiv \int_{\Omega_1} Q(d\omega) \int_{\mathcal{C}_n} d\mathbb{P}^{\alpha(\omega)} \quad (2.8)$$

$$\geq \int_{G_n} Q(d\omega) \int_{\mathcal{C}_n} d\mathbb{P}^{\alpha(\omega)}. \quad (2.9)$$

So assume that $Q[G_n] \equiv e_1(n) \geq 1 - \phi_1(n)$ and assume that for all $\omega \in G_n$, $\int_{\mathcal{C}_n} d\mathbb{P}^{\alpha(\omega)} \equiv e_2(\omega, n) \geq 1 - \phi_2(n)$ we get that

$$\mathbb{P}[\mathcal{C}_n] \geq e_1(n) \times \min_{w \in G_n} (e_2(w, n)) \geq 1 - \phi_1(n) - \phi_2(n). \quad (2.10)$$

2.2 Arguments for the walk

Let $(\rho_1(n), n \in \mathbb{N})$ a strictly positive decreasing sequence such that $\lim_{n \rightarrow \infty} \rho_1(n) = 0$. First let us show that the Theorem 1.8 is a simple consequence of the following

Proposition 2.5. *Assume 1.2, 1.3 and 1.4 hold, there exists n_0 such that for all $n > n_0$ there exists $G_n \subset \Omega_1$ with $Q[G_n] \geq 1 - \phi_1(n)$ and*

$$\sup_{\alpha \in G_n} \left\{ \mathbb{P}_0^\alpha \left[\bigcup_{k \in \mathbb{L}_n^\gamma} \left\{ \left| \frac{\mathcal{L}(k, n)}{n} - \frac{E_{m_n}^\alpha(k)}{E_{m_n}^\alpha(W_n)} \right| \leq w_{k, n} \right\} \right] \right\} \geq 1 - \phi_2(n) \quad (2.11)$$

where $w_{k, n} = \rho_1(n) \frac{E_{m_n}^\alpha(k)}{E_{m_n}^\alpha(W_n)}$, $\phi_1(n)$ and $\phi_2(n)$ are given just after 1.28

Taking the logarithm and using its Taylor serie for n large enough, we remark that

$$-\rho_1(n) \frac{E_{m_n}^\alpha(k)}{E_{m_n}^\alpha(W_n)} \leq \frac{\mathcal{L}(k, n)}{n} - \frac{E_{m_n}^\alpha(k)}{E_{m_n}^\alpha(W_n)} \leq \rho_1(n) \frac{E_{m_n}^\alpha(k)}{E_{m_n}^\alpha(W_n)} \quad (2.12)$$

is equivalent to

$$-2\rho_1(n) - \log(E_{m_n}^\alpha(W_n)) \leq \log \mathcal{L}(k, n) - \log n - \log(E_{m_n}^\alpha(k)) \leq -\log(E_{m_n}^\alpha(W_n)) + \rho_1(n) \quad (2.13)$$

rearranging the terms and using A.1 (Appendix Lemma A.1) we get

$$\frac{1}{\log n} (R_n^\alpha(k) - 2\rho_1(n)) \leq \hat{S}_k^n - S_{k, m_n}^n \leq \frac{1}{\log n} (R_n^\alpha(k) - \rho_1(n)) \quad (2.14)$$

where $R_n^\alpha(k) = \log \left(\frac{\alpha m_n}{\beta_k} a_{k, m_n} \right) - \log(E_{m_n}^\alpha(W_n))$ and a_{k, m_n} is given by A.2. Now using A.4 and Property 2.5 we get the Theorem. The proof of Proposition 2.5 is based on the following results (Lemma 2.6) of [Andreoletti(2005)],

2.2.1 Known facts

Let where $\rho(n)$ a positive decreasing sequence such that $\lim_{n \rightarrow \infty} \rho(n) = 0$, we define

$$\mathcal{A}_1 = \left\{ \left| \frac{\mathcal{L}(m_n, n)}{n} - \frac{1}{E_{m_n}^\alpha(W_n)} \right| > \frac{\rho(n)}{E_{m_n}^\alpha(W_n)} \right\}, \quad (2.15)$$

$$\mathcal{A}_2 = \{T_{m_n} \leq n/(\log n)^4, \mathcal{L}(W_n, n) = 1\}. \quad (2.16)$$

Lemma 2.6. *Assume 1.2, 1.3 and 1.4 hold, there exists a constant $b_1 > 0$ such that for all $\gamma > 6$, there exists n_0 such that for all $n > n_0$ there exists $G_n \subset \Omega_1$ with $Q[G_n] \geq 1 - \phi_1(n)$ and*

$$\sup_{\alpha \in G'_n} \{\mathbb{P}_0^\alpha [\mathcal{A}_1]\} \leq r_1(n), \quad (2.17)$$

where $r_1(n) = b_1/(\log n)^{\gamma-6}$.

Proof.

We do not give the details of the computations because the reader can find it in the referenced paper (Theorem 3.8 of [Andreoletti(2006)]), just notice that comparing to the Theorem 3.8 we have a better rate of convergence for the probability because we have used a weaker result for the concentration of the walk. ■

We will also need the following elementary fact :

Lemma 2.7. *Assume 1.2, 1.3 and 1.4 hold, there exists a constant $b_2 > 0$ such that for all $\gamma > 2$, there exists n_0 such that for all $n > n_0$ there exists $G_n \subset \Omega_1$ with $Q[G_n] \geq 1 - \phi_1(n)$ and*

$$\sup_{\alpha \in G'_n} \{\mathbb{P}_0^\alpha [\mathcal{A}_2]\} \leq r_2(n), \quad (2.18)$$

where $r_2(n) = b_2/(\log n)^{\gamma-2}$.

Proof.

Once again this can be find in [Andreoletti(2006)]: Proposition 4.7 and Lemma 4.8. ■

Using these results we can give the proof of Proposition 2.5 in two steps :

2.2.2 Step 1

Let us define the following subsets :

$$\bar{v}_1^n \equiv \{k \in \mathbb{Z}, S_k - S_{m_n} \leq \log n - \gamma/2 \log_2 n\} \quad (2.19)$$

$$\bar{v}_2^n \equiv \{k \in \mathbb{Z}, \log n - (\max_{k \leq j \leq m_n} S_j - S_{m_n}) > \gamma \log_2 n\} \quad (2.20)$$

and

$$V_n^\gamma = \bar{v}_1^n \cap \bar{v}_2^n \cap W_n. \quad (2.21)$$

In words \bar{v}_1^n implies that the difference of potential between an arbitrary k and m_n is smaller than $\log n - \gamma/2 \log_2 n$, for the walk this means that we can be sharp for the potential only if the walk starting from m_n can hit k a number of time large enough. \bar{v}_2^n has almost the same meaning and says that the largest difference of potential between m_n and k must be smaller than $\log n - \gamma/2 \log_2 n$, for the walk this means that the walk will hit k again even after it has reach m_n (see figure 5 and 6).

First let us prove the following Lemma :

Lemma 2.8. *Assume 1.2, 1.3 and 1.4 hold, there exists a constant $b_3 > 0$ such that for all $\gamma > 6$, there exists n_0 such that for all $n > n_0$ there exists $G_n \subset \Omega_1$ with $Q[G_n] \geq 1 - \phi_1(n)$*

$$\sup_{\alpha \in G'_n} \{\mathbb{P}_0^\alpha [\mathbb{L}_n^\gamma \subset V_n^\gamma]\} \geq 1 - r_3(n), \quad (2.22)$$

where $r_3(n) = b_3/(\log n)^{\gamma/2}$.

Notice that \mathbb{L}_n^γ is a \mathbb{P} random variable whereas V_n^γ is only a Q random variable, this Lemma makes the link between a trajectory of the walk and the random environment.

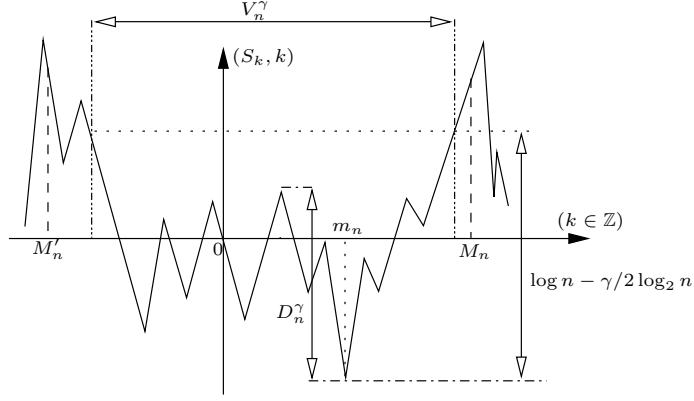


Figure 5: V_n^γ with $m_n > 0$, case 1: $D_n^\gamma \equiv \max_{k \in \bar{v}_1} \max_{k \leq j \leq m_n} (S_j - S_{m_n}) \leq \log n - \gamma \log_2 n$

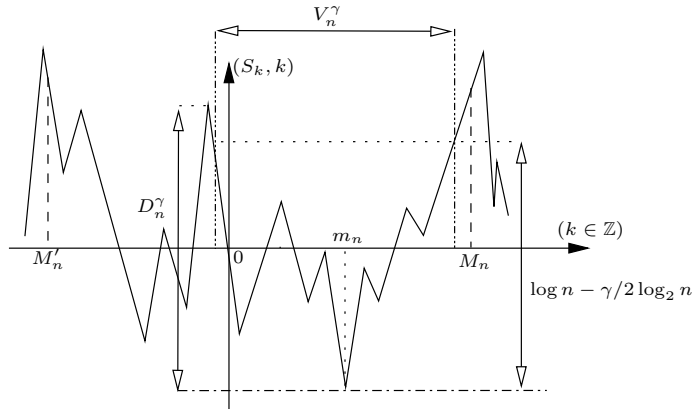


Figure 6: V_n^γ with $m_n > 0$, case 2: $D_n^\gamma \equiv \max_{k \in \bar{v}_1} \max_{k \leq j \leq m_n} (S_j - S_{m_n}) > \log n - \gamma \log_2 n$

Proof.

To prove this Lemma we use Proposition 1.9. First notice that

$$\mathbb{P}_0^\alpha [\mathbb{L}_n^\gamma \subset V_n^\gamma] = 1 - \mathbb{P}_0^\alpha \left[\bigcup_{k \in (v_n^1 \cup v_n^2)} \{k \in \mathbb{L}_n\} \right] \quad (2.23)$$

where

$$v_1^n = \{k \in \mathbb{Z}, S_k - S_{m_n} > \log n - \gamma/2 \log_2 n\}, \quad (2.24)$$

$$v_2^n = \{k \in \mathbb{Z}, \log n - (\max_{k \leq j \leq m_n} S_j - S_{m_n}) \leq \gamma \log_2 n\}. \quad (2.25)$$

. Let $k \in v_1^n$ let us give an upper bound for

$$\begin{aligned}
\mathbb{P}_0^\alpha [k \in \mathbb{L}_n, |T_{k^*} - T_{m_n}| \leq (\log n)^3] &\leq \mathbb{P}_0^\alpha \left[\sum_{j=T_{k^*}}^n \mathbb{I}_{X_j=k} \geq (\log n)^\gamma, |T_{k^*} - T_{m_n}| \leq (\log n)^3 \right] \\
&\leq \mathbb{P}_0^\alpha \left[\sum_{j=T_{m_n}}^n \mathbb{I}_{X_j=k} \geq (\log n)^\gamma - (\log n)^3 \right] \\
&\leq \mathbb{P}_{m_n}^\alpha \left[\sum_{j=1}^{T_{m_n,n}} \mathbb{I}_{X_j=k} \geq (\log n)^\gamma - (\log n)^3 \right], \tag{2.26}
\end{aligned}$$

for the third inequality we have used the strong Markov property and that for all $j \geq 2$

$$\begin{aligned}
T_{m_n,j} &\equiv \begin{cases} \inf\{k > T_{m_n,j-1}, X_k = m_n\}, \\ +\infty, \text{ if such } k \text{ does not exist.} \end{cases} \\
T_{m_n,1} &\equiv T_{m_n} \text{ (see 1.23).}
\end{aligned}$$

Now using the Markov inequality and Lemma A.1 we get

$$\mathbb{P}_0^\alpha [k \in \mathbb{L}_n, |T_{k^*} - T_{m_n}| \leq (\log n)^3] \leq \frac{n \mathbb{E}_{m_n}^\alpha [\mathcal{L}(k, T_{m_n})]}{(\log n)^\gamma - \log n} \tag{2.27}$$

$$\leq \frac{n}{\eta_0 \exp(S_k - S_{m_n}) ((\log n)^\gamma - (\log n)^3)} \tag{2.28}$$

$$\leq \frac{1}{\eta_0 (\log n)^{\gamma/2} (1 - (\log n)/(\log n)^\gamma)}, \tag{2.29}$$

notice that in the last inequality we have used the fact that $k \in v_1^n$. Now let $k \in v_2^n$, let us give an upper bound for

$$\begin{aligned}
&\mathbb{P}_0^\alpha [k \in \mathbb{L}_n, |T_{k^*} - T_{m_n}| \leq (\log n)^3] \\
&\leq \mathbb{P}_0^\alpha \left[\sum_{j=T_{m_n}}^n \mathbb{I}_{X_j=k} > (\mathcal{L}(k, T_{m_n})) \vee (\log n)^\gamma - (\log n)^3 \right] \tag{2.30}
\end{aligned}$$

Let us denote $g(n) = \exp(\max_{k \leq j \leq m_n-1} (S_j - S_k)) (\log n)^{-\gamma/2}$. It is easy to check that

$$\mathbb{P}_0^\alpha [\mathcal{L}(k, T_{m_n}) \geq g(n)] \geq 1 - \frac{1}{\eta_0 (\log n)^{\gamma/2}}. \tag{2.31}$$

Now denote $g'(n) = g(n) \vee (\log n)^\gamma - (\log n)^3$, we have :

$$\mathbb{P}_0^\alpha \left[\sum_{j=T_{m_n}}^n \mathbb{I}_{X_j=k} > g'(n) \right] \leq \mathbb{P}_{m_n}^\alpha \left[\sum_{j=1}^{T_{m_n,n}} \mathbb{I}_{X_j=k} > g'(n) \right] \tag{2.32}$$

$$\leq \frac{n \mathbb{E}_{m_n}^\alpha [\mathcal{L}(k, T_{m_n})]}{g'(n)}, \tag{2.33}$$

for the first inequality we have used that $T_{m_n} \geq 0$ and $T_{m_n, n} \geq n$ and for the second one the Markov inequality. Using Lemma A.1 we know that $\mathbb{E}_{m_n}^\alpha [\mathcal{L}(k, T_{m_n})] \leq (\eta_0 \exp(S_k - S_{m_n}))^{-1}$ and using that $k \in v_2^n$ we get that

$$\mathbb{P}_0^\alpha [k \in \mathbb{L}_n, |T_{k^*} - T_{m_n}| \leq (\log n)^3] \leq \frac{1}{\eta_0 (\log n)^{\gamma/2} (1 - (\log n)^3 / (\log n)^{\gamma/2})}. \quad (2.34)$$

Collecting what we did above, and using 1.32 we get the Lemma. \blacksquare

2.2.3 Step 2

This second step is devoted to the proof of the following Lemma.

Lemma 2.9. *For all α and n we have*

$$\mathbb{P}_0^\alpha \left[\left| \frac{\mathcal{L}(k, n)}{n} - \frac{E_{m_n}^\alpha(k)}{E_{m_n}^\alpha(W_n)} \right| > w_{k, n}, \mathcal{A}_1, \mathcal{A}_2 \right] \leq 2 \exp(-n/2\psi_2^\alpha(n)) \quad (2.35)$$

recall that $w_{k, n} = \rho_1(n) \frac{E_{m_n}^\alpha(k)}{E_{m_n}^\alpha(W_n)}$ and $\psi_2^\alpha(n) = 2 \frac{(\rho_1(n) - \rho(n))^2}{1 + \rho(n)} \frac{(\alpha_{m_n} \wedge \beta_{m_n}) \exp(-S_{M_k} - S_{m_n})}{|k - m_n| E_{m_n}^\alpha(W_n)}$. M_k is such that $S_{M_k} = \max_{m_n+1 \leq j \leq k} S_j$ if $k > m_n$ and conversly if $k < m_n$ $S_{M_k} = \max_{k \leq j \leq m_n-1} S_j$.

Proof.

We essentially use an inequality of concentration (see [Ledoux(2001)]), for simplicity we only give the proof for $k > m_n$, the other case ($k \leq m_n$) is very similar. Using the Markov property and the fact that $\mathcal{L}(k, T_{m_n}) = 0$, we get

$$\mathbb{P}_0^\alpha \left[\left| \frac{\mathcal{L}(k, n)}{n} - \frac{E_{m_n}^\alpha(k)}{E_{m_n}^\alpha(W_n)} \right| > w_{k, n}, \mathcal{A}_1, \mathcal{A}_2 \right] \leq \mathbb{P}_{m_n}^\alpha \left[\left| \frac{\mathcal{L}(k, n)}{n} - \frac{E_{m_n}^\alpha(k)}{E_{m_n}^\alpha(W_n)} \right| > w_{k, n}, \mathcal{A}_1 \right] \quad (2.36)$$

We have

$$\begin{aligned} & \mathbb{P}_{m_n}^\alpha \left[\frac{\mathcal{L}(k, n)}{n} - \frac{E_{m_n}^\alpha(k)}{E_{m_n}^\alpha(W_n)} > w_{k, n}, \mathcal{A}_1 \right] \\ & \leq \mathbb{P}_{m_n}^\alpha \left[\frac{\mathcal{L}(k, n)}{n} - \frac{E_{m_n}^\alpha(k)}{E_{m_n}^\alpha(W_n)} > w_{k, n}, \frac{\mathcal{L}(m_n, n)}{n} - \frac{1}{E_{m_n}^\alpha(W_n)} \leq \frac{\rho(n)}{E_{m_n}^\alpha(W_n)} \right] \end{aligned} \quad (2.37)$$

$$\leq \mathbb{P}_{m_n}^\alpha \left[\frac{\mathcal{L}(k, T_{m_n, n_1})}{n} - \frac{E_{m_n}^\alpha(k)}{E_{m_n}^\alpha(W_n)} > w_{k, n} \right] \quad (2.38)$$

$$\equiv \mathbb{P}_{m_n}^\alpha \left[\frac{\mathcal{L}(k, T_{m_n, n_1})}{n} - \frac{E_{m_n}^\alpha(k)}{E_{m_n}^\alpha(W_n)} (1 + \rho(n)) > w'_{k, n} \right] \quad (2.39)$$

where $n_1 = \frac{n}{E_{m_n}^\alpha(W_n)} (1 + \rho(n))$, actually n_1 is not necessarily an integer but for simplicity we disregard that, and $w'_{k, n} = \frac{E_{m_n}^\alpha(k)}{E_{m_n}^\alpha(W_n)} (\rho_1(n) - \rho(n))$. The strong Markov property implies that $\mathcal{L}(k, T_{m_n, n_1})$ is a sum of n_1 i.i.d. random variables, the inequality of concentration gives

$$\mathbb{P}_{m_n}^\alpha \left[\frac{\mathcal{L}(k, T_{m_n, n_1})}{n} - \frac{E_{m_n}^\alpha(k)}{E_{m_n}^\alpha(W_n)} > w'_{k, n}, \mathcal{A}_1 \right] \leq \exp \left[-\frac{n}{2} \frac{E_{m_n}^\alpha(W_n)}{\text{Var}_{m_n}(\mathcal{L}(k, T_{m_n}))} \frac{(w'_{k, n})^2}{1 + \rho(n)} \right]. \quad (2.40)$$

With the same method we also get

$$\mathbb{P}_{m_n}^\alpha \left[\frac{\mathcal{L}(k, T_{m_n, n_1})}{n} - \frac{E_{m_n}^\alpha(k)}{E_{m_n}^\alpha(W_n)} < -w'_{k, n}, \mathcal{A}_1 \right] \leq \exp \left[-\frac{n}{2} \frac{E_{m_n}^\alpha(W_n)}{\text{Var}_{m_n}(\mathcal{L}(k, T_{m_n}))} \frac{(w'_{k, n})^2}{1 + \rho(n)} \right] \quad (2.41)$$

Using A.3 we get Lemma 2.9. \blacksquare

2.2.4 End of the proof of the Theorem

Using Lemmata 2.6, 2.7 and 2.8 we have:

$$\begin{aligned} & \mathbb{P}_0^\alpha \left[\bigcup_{k \in \mathbb{L}_n^\alpha} \left\{ \left| \frac{\mathcal{L}(k, n)}{n} - \frac{E_{m_n}^\alpha(k)}{E_{m_n}^\alpha(W_n)} \right| > w_{k, n} \right\} \right] \\ & \leq |V_n^\gamma| \sup_{k \in V_n^\gamma} \mathbb{P}_0^\alpha \left[\left| \frac{\mathcal{L}(k, n)}{n} - \frac{E_{m_n}^\alpha(k)}{E_{m_n}^\alpha(W_n)} \right| > w_{k, n}, \mathcal{A}_1, \mathcal{A}_2 \right] + 3 \max_{1 \leq i \leq 3} \{r_i(n)\}, \end{aligned}$$

then using Lemma 2.9 we get

$$\begin{aligned} \sup_{k \in V_n^\gamma} \mathbb{P}_0^\alpha \left[\left| \frac{\mathcal{L}(k, n)}{n} - \frac{E_{m_n}^\alpha(k)}{E_{m_n}^\alpha(W_n)} \right| > w_{k, n}, \mathcal{A}_1, \mathcal{A}_2 \right] & \leq 2 \sup_{k \in V_n^\gamma} \exp(-n/2\psi_2^\alpha(k, n)) \\ & \leq 2 \exp(-(\log n)^{\gamma/2-2}/(\rho_1(n) \log_2 n)), \end{aligned} \quad (2.42)$$

where the last inequality comes from the definition of V_n^γ (see 2.21) and the Properties 2.5 and 2.4. To end we use again the Property 2.4 together with the definition of V_n^γ .

3 Sketch of proof of Proposition 1.9 and 1.10

1.31 is an optimization of Corollary 3.17 of [Andreoletti(2006)] so we get a better convergence for the probability. To get 1.32, we have used the same idea of the proof of Corollary 3.17 of [Andreoletti(2006)], so once again we will not repeat the computations here. The intuitive idea is that once the walk has reached k^* , we know from 1.31 that m_n is at most at a distance $(\log_2 n)^2$, therefore the walk need at most $\exp(\sqrt{(\log_2 n)^2}) = (\log n)$ to reach the end of the interval. We take $(\log n)^3$ for a technical reason.

4 Algorithm and Numerical simulations

4.1 General and recall of the main definitions

First notice that we have no criteria to determine wether or not we can apply this method to an unknown series of data. All we know is that it works for Sinai's walk, however we can apply the following algorithm to every process. Let us recall the basic random variables that will be used for our simulations, let $x \in \mathbb{Z}$, $n \in \mathbb{N}$,

$$T_x = \begin{cases} \inf\{k \in \mathbb{N}^*, X_k = x\} \\ +\infty, \text{ if such } k \text{ does not exist.} \end{cases} \quad (4.1)$$

$$\mathcal{L}(x, n) \equiv \sum_{i=1}^n \mathbb{I}_{\{X_i=x\}}, \quad (4.2)$$

$$\mathcal{L}^*(n) = \max_{k \in \mathbb{Z}} (\mathcal{L}(k, n)), \quad \mathbb{F}_n = \{k \in \mathbb{Z}, \mathcal{L}(k, n) = \mathcal{L}^*(n)\}, \quad (4.3)$$

$$k^* = \inf\{|k|, k \in \mathbb{F}_n\}. \quad (4.4)$$

$$(4.5)$$

We recall also the set \mathbb{L}_n^γ , the function of the potential we want to estimate and its estimator:

$$\mathbb{L}_n^\gamma = \left\{ k \in \mathbb{Z}, \sum_{j=T_{k^*}}^n \mathbb{I}_{X_j=k} \geq ((\log n)^\gamma) \vee (\mathcal{L}(k, T_{k^*})) \right\}, \quad (4.6)$$

$$S_{k, m_n}^n = 1 - \frac{1}{\log n} (S_k - S_{m_n}), \quad (4.7)$$

$$\hat{S}_k^n = \frac{\log(\mathcal{L}(k, n))}{\log n}, \quad (4.8)$$

We also recall that thanks to Proposition 1.9, in probability we have $m_n - k^* \leq O(\log_2 n)^2$.

4.2 Main steps of the algorithm

Step 1: We have to determine \mathbb{L}_n^γ and to get it we have to compute T_{k^*} and therefore the local time of the process. First we compute $\mathcal{L}(k, n)$ for every k , notice that $\mathcal{L}(k, n)$ is not equal to zero only if k has been visited by the walk within the interval of time $[1, n]$. Then we can compute $\mathcal{L}^*(n)$ and determine k^* and T_{k^*} . Notice that T_{k^*} is not a stopping time. We are now able to determine \mathbb{L}_n^γ computing $\sum_{j=T_{k^*}}^n \mathbb{I}_{X_j=k}$ and $\mathcal{L}(k, T_{k^*})$.

Step 2: We can check that \mathbb{L}_n^γ is connex, contains k^* and that its size is of the order of a typical fluctuation of the walk. Now, keeping only the k that belongs to \mathbb{L}_n^γ we compute for those k : $\hat{S}_k^n = \frac{\log(\mathcal{L}(k, n))}{\log n}$ the estimator of the potential. We localize the bottom of the valley m_n using k^* .

4.3 Simulations

For the first simulation we show a case where \mathbb{L}_n^γ is large i.e. \mathbb{L}_n^γ contains most of the points visited by the walk. The trajectory of the random potential is in red the interval of confidence in blue and

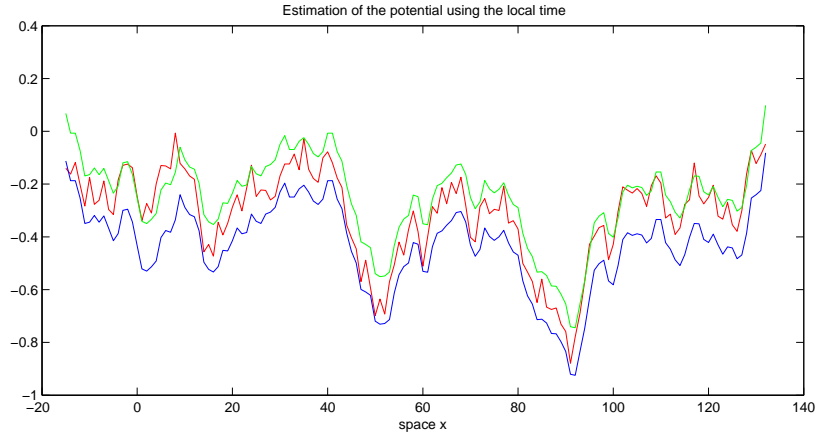


Figure 7: in red S_{x, m_n}^n , in blue $\hat{S}_x^n - u_n$, in green $\hat{S}_x^n + u_n$

green. We took $n = 500000$ and $\gamma = 7$, notice that the larger is γ , the is smaller \mathbb{L}_n^γ but better is the rate of convergence of the probability. We get that $\mathbb{L}_n^\gamma = [10, 94]$. In the next figure we plot the

difference $S_{x,m_n}^n - \hat{S}_x^n$ and its the linear regression. We notice that the slope of the linear regression is

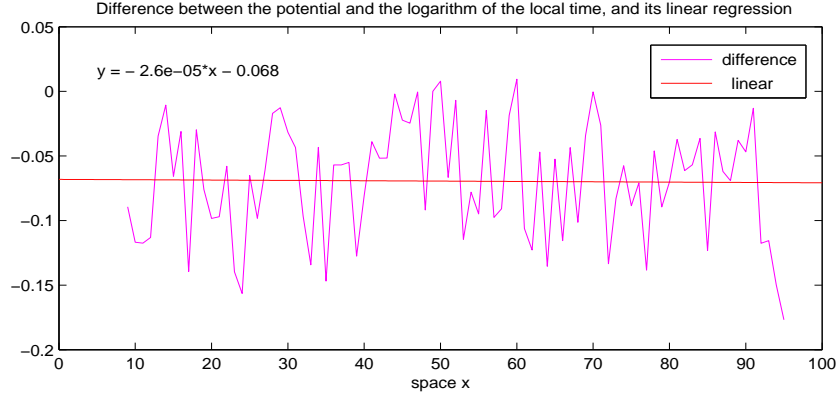


Figure 8: in magenta $S_{x,m_n}^n - \hat{S}_x^n$, in red the linear regression

of order 10^{-5} , and therefore almost null. We also notice that we take $n = 500000$, and therefore the error function $u_n \approx \frac{\log_3 n}{\log n} \approx 0,7$ this match with the $\max_x (S_{x,m_n}^n - \hat{S}_x^n) \approx 0.8$ for this simulation. Now let us choose another example where \mathbb{L}_n^γ is much more smaller. For the following simulation we have only changed the sequence of random number. We get that $\mathbb{L}_n^\gamma = [-150, -85]$. We notice that for

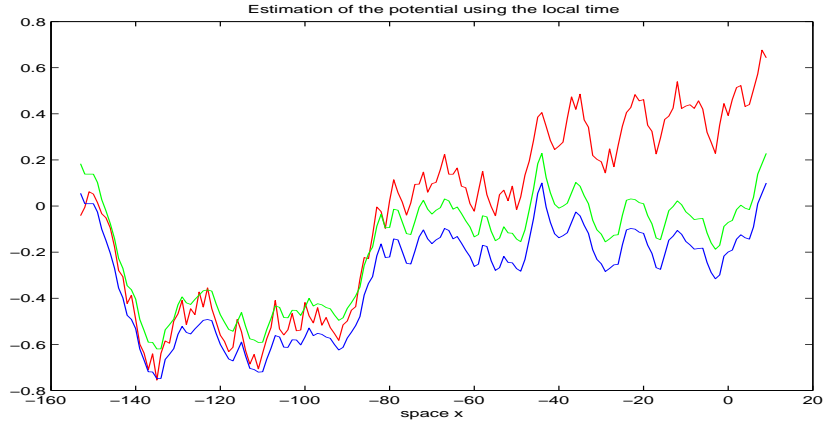


Figure 9: in red S_{x,m_n}^n , in blue $\hat{S}_x^n - u_n$, in green $\hat{S}_x^n + u_n$

the coordinates larger than -85 and especially after -40, our estimator is not good at all. In fact once the walk has reached the minimum of the valley (coordinate -111) it will never reach again one of the points of coordinate larger than -40 before $n = 500000$, so our estimator can not say anything about the difference $S_{x,m_n}^n - \hat{S}_x^n$. However if we look in the past of the walk and especially at a the time T^* which is the first time it has reached the coordinate -111, the favorite point for this time is localized around the point -2, so a good estimator between the coordinate -40 and 10 is given by $\frac{\log(\mathcal{L}(k,T^*))}{\log T^*}$.

For the difference $S_{x,m_n}^n - \hat{S}_x^n$ and the linear regression in the interval $\mathbb{L}_n^\gamma = [-150, -85]$ we get:

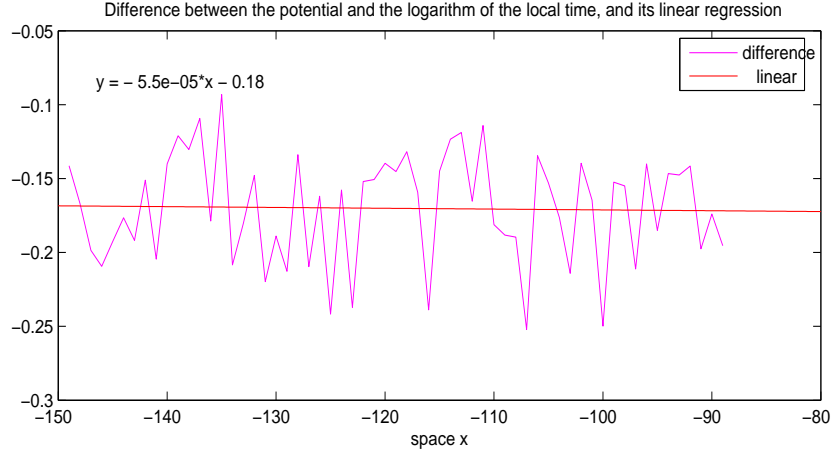


Figure 10: in magenta $S_{x,m_n}^n - \hat{S}_x^n$, in red the linear regression

A Basic results for birth and death processes

For completeness we recall an explicit expression for the mean and an upper bound for the variance of the local times at a certain stopping time, we can be found a proof of these elementary facts in [Révész(1989)] (page 279)

Lemma A.1. *For all α , Let $k > m_n$*

$$\mathbb{E}_{m_n}^\alpha [\mathcal{L}(k, T_{m_n})] = \frac{\alpha_{m_n}}{\beta_k} \frac{1}{e^{S_k - S_{m_n}}} a_{k,m_n}, \text{ where} \quad (\text{A.1})$$

$$a_{k,m_n} = \frac{\sum_{i=m_n+1}^{k-1} e^{S_i} + e^{S_k}}{\sum_{i=m_n+1}^{k-1} e^{S_i} + e^{S_{m_n}}}. \quad (\text{A.2})$$

$$\text{Var}_{m_n} [\mathcal{L}(k, T_{m_n})] \leq 2\mathbb{E}_{m_n}^\alpha [\mathcal{L}(k, T_{m_n})] \frac{e^{S_{M_k} - S_k}}{\beta_k} |k - m_n|. \quad (\text{A.3})$$

M_k is such that $S_{M_k} = \max_{m_n+1 \leq j \leq k} S_j$. For Q -a.a. environment α

$$\frac{\eta_0}{1 - \eta_0} \leq \frac{\alpha_{m_n}}{\beta_k} a_{k,m_n} \leq \frac{1}{\eta_0}. \quad (\text{A.4})$$

A similar result is true for $k < m_n$ and $\mathbb{E}_{m_n}^\alpha [\mathcal{L}(k, T_{m_n})] = 1$.

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