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Directed polymer in random environment and last passage percolation*

Philippe Carmona[†]

<http://www.math.sciences.univ-nantes.fr/~carmona>

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Abstract

The sequence of random probability measures ν_n that gives a path of length n , $\frac{1}{n}$ times the sum of the random weights collected along the paths, is shown to satisfy a large deviations principle with good rate function the Legendre transform of the free energy of the associated directed polymer in a random environment.

Consequences on the asymptotics of the typical number of paths whose collected weight is above a fixed proportion are then drawn.

Keywords: directed polymer, random environment, partition function, last passage percolation.

Mathematic Classification : 60K37

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[†]Laboratoire Jean Leray, UMR 6629 Université de Nantes, BP 92208, F-44322 Nantes Cedex 03

1 Introduction

Last passage percolation

To each site (k, x) of $\mathbb{N} \times \mathbb{Z}^d$ is assigned a random weight $\eta(k, x)$. The $(\eta(k, x))_{k \geq 1, x \in \mathbb{Z}^d}$ are taken IID under the probability measure \mathbf{Q} . The set of oriented paths of length n starting from the origin is

$$\Omega_n = \left\{ \omega = (\omega_0, \dots, \omega_n) : \omega_i \in \mathbb{Z}^d, \omega_0 = 0, |\omega_i - \omega_{i-1}| = 1 \right\}.$$

The weight (energy, reward) of a path is the sum of weights of visited sites:

$$H_n = H_n(\omega, \eta) = \sum_{k=1}^n \eta(k, \omega_k) \quad (n \geq 1, \omega \in \Omega_n).$$

Observe that when $\eta(k, x)$ are Bernoulli(p) distributed

$$\mathbf{Q}(\eta(k, x) = 1) = 1 - \mathbf{Q}(\eta(k, x) = 0) = p \in (0, 1),$$

the quantity $\frac{H_n}{n}(\omega, \eta)$ is the proportion of *open* sites visited by ω , and it is natural to consider for $p < \rho < 1$,

$$N_n(\rho) = \text{number of paths of length } n \text{ such that } H_n(\omega, \eta) \geq n\rho.$$

The problem of ρ -percolation, as we learnt it from Comets, Popov and Vachkovskaia [8] and Kesten and Sidoravicius [12], is to study the behaviour of $N_n(\rho)$ for large n .

Directed polymer in a random environment

We are going to consider fairly general environment distributions, by requiring first that they have exponential moments of any order:

$$\lambda(\beta) = \log \mathbf{Q} \left(e^{\beta \eta(k, x)} \right) < +\infty \quad (\beta \in \mathbb{R}),$$

and second that they satisfy a logarithmic Sobolev inequality (see e.g. [2]): in particular we can apply our result to bounded support and Gaussian environments.

The polymer measure is the random probability measure defined on the set of oriented paths of length n by:

$$\mu_n(\omega) = (2d)^{-n} \frac{e^{\beta H_n(\omega, \eta)}}{Z_n(\beta)} \quad (\omega \in \Omega_n),$$

with $Z_n(\beta)$ the partition function

$$Z_n(\beta) = Z_n(\beta, \eta) = (2d)^{-n} \sum_{\omega \in \Omega_n} e^{\beta H_n(\omega, \eta)} = \mathbf{P} \left(e^{\beta H_n(\omega, \eta)} \right),$$

where \mathbf{P} is the law of simple random walk on \mathbb{Z}^d starting from the origin. Bolthausen [3] proved the existence of a deterministic limiting free energy

$$p(\beta) = \lim_{n \rightarrow +\infty} \frac{1}{n} \mathbf{Q}(\log Z_n(\beta)) = \mathbf{Q} \text{ a.s. } \lim_{n \rightarrow +\infty} \frac{1}{n} \log Z_n(\beta).$$

Thanks to Jensen's inequality, we have the upper bound $p(\beta) \leq \lambda(\beta)$ and it is conjectured (and partially proved, see [7, 6]) that the behaviour of a typical path under the polymer measure is diffusive iff $\beta \in \mathcal{C}_\eta$ the critical region

$$\mathcal{C}_\eta = \{\beta \in \mathbb{R} : p(\beta) = \lambda(\beta)\}.$$

In dimension $d = 1$, $\mathcal{C}_\eta = \{0\}$ and in dimensions $d \geq 3$, \mathcal{C}_η contains a neighborhood of the origin (see [3, 9]).

The main theorem

The connection between Last passage percolation and Directed polymer in random environment is made by the family $(\nu_n)_{n \in \mathbb{N}}$ of random probability measures on the real line:

$$\nu_n(A) = \frac{1}{|\Omega_n|} \sum_{\omega \in \Omega_n} \mathbf{1}_{(\frac{H_n}{n}(\omega, \eta) \in A)} = \mathbf{P} \left(\frac{H_n}{n}(\omega, \eta) \in A \right).$$

Indeed,

$$N_n(\rho) = \sum_{\omega \in \Omega_n} \mathbf{1}_{(H_n(\omega, \eta) \geq n\rho)} = (2d)^n \nu_n([\rho, +\infty)).$$

The main result of the paper is

Theorem 1. *\mathbf{Q} almost surely, the family $(\nu_n)_{n \in \mathbb{N}}$ satisfies a large deviations principle with good rate function $I = p^*$ the Legendre transform of the free energy of the directed polymer.*

Let $m = \mathbf{Q}(\eta(k, x))$ be the average weight of a path $m = \mathbf{Q}(\frac{H_n}{n}(\omega, \eta))$. It is natural to consider the quantities:

$$N_n(\rho) = \begin{cases} \sum_{\omega \in \Omega_n} \mathbf{1}_{(H_n(\omega, \eta) \geq n\rho)} & \text{if } \rho \geq m, \\ \sum_{\omega \in \Omega_n} \mathbf{1}_{(H_n(\omega, \eta) \leq n\rho)} & \text{if } \rho < m. \end{cases}$$

A simple exchange of limits $\beta \rightarrow \pm\infty$, and $n \rightarrow +\infty$, yields the following

$$\rho^\pm = \mathbf{Q} \text{ a.s. } \lim_{n \rightarrow +\infty} \max_{\omega \in \Omega_n} \pm \frac{H_n}{n}(\omega, \eta) = \lim_{\beta \rightarrow +\infty} \frac{p(\pm\beta)}{\beta} \in [0, +\infty].$$

Repeating the proof of Theorem 1.1 of [8] gives

Corollary 2. *For $-\rho^- < \rho < \rho^+$, we have \mathbf{Q} almost surely,*

$$\lim_{n \rightarrow +\infty} (N_n(\rho))^{\frac{1}{n}} = (2d)e^{-I(\rho)}.$$

We can then translate our knowledge of the critical region \mathcal{C}_η , into the following remark. Let

$$\mathcal{V}_\eta = \{\rho \in \mathbb{R} : I(\rho) = \lambda^*(\rho)\}.$$

In dimension $d = 1$, $\mathcal{V}_\eta = \{m\}$ and in dimensions $d \geq 3$, \mathcal{V}_η contains a neighbourhood of m .

This means that in dimensions $d \geq 3$, the typical large deviation of $\frac{H_n}{n}(\omega, \eta)$ close to its mean is the same as the large deviation of $\frac{1}{n}(\eta_1 + \dots + \eta_n)$ close to its mean, with η_i IID. There is no influence of the path ω : this gives another justification to the name weak-disorder region given to the critical set \mathcal{C}_η .

2 Proof of the main theorem

Observe that for any $\beta \in \mathbb{R}$ we have:

$$\int e^{\beta n x} d\nu_n(x) = \mathbf{P} \left(e^{\beta H_n(\omega, \eta)} \right) = Z_n(\beta) \quad \mathbf{Q} \text{ a.s.} \quad (1)$$

Consequently, since $e^u + e^{-u} \geq e^{|u|}$, we obtain for any $\beta > 0$,

$$\limsup_{n \rightarrow +\infty} \frac{1}{n} \log \left(\int e^{\beta n |x|} d\nu_n(x) \right) \leq p(\beta) + p(-\beta) < +\infty,$$

and the family $(\nu_n)_{n \geq 0}$ is exponentially tight (see the Appendix, Lemma 3). We only need to show now that for a lower semicontinuous function I , and for $x \in \mathbb{R}$

$$\lim_{\delta \rightarrow 0} \liminf_{n \rightarrow \infty} \frac{1}{n} \log \nu_n((x - \delta, x + \delta)) = -I(x), \quad (2)$$

$$\lim_{\delta \rightarrow 0} \limsup_{n \rightarrow \infty} \frac{1}{n} \log \nu_n([x - \delta, x + \delta]) = -I(x). \quad (3)$$

From these, we shall infer that $(\nu_n)_{n \in \mathbb{N}}$ follows a large deviations principle with good rate function I . Eventually, equation (1) and

$$\lim_{n \rightarrow \infty} \frac{1}{n} \log Z_n(\beta) = p(\beta)$$

will imply, by Varadhan's lemma that I and p are Legendre conjugate:

$$I(x) = p^*(x) = \sup_{\beta \in \mathbb{R}} (x\beta - p(\beta)).$$

The strategy of proof finds its origin in Varadhan's seminal paper [13], and has already successfully been applied in [5]. Let us define for $\lambda > 0, x \in \mathbb{Z}, a \in \mathbb{R}$

$$V_n^{(\lambda)}(x, a; \eta) = \log \mathbf{P}^x \left(e^{-\lambda |H_n(\omega, \eta) - a|} \right) = V^{(\lambda)}(0, a; \tau_{0,x} \circ \eta),$$

with $\tau_{k,x}$ the translation operator on the environment defined by :

$$\tau_{k,x} \circ \eta(i, y) = \eta(k + i, x + y),$$

and \mathbf{P}^x the law of simple random walk starting from x .

Step 1 The functions $v_n^{(\lambda)}(a) = \mathbf{Q}(V^{(\lambda)}(0, a; \eta))$ satisfy the inequality

$$v_{n+m}^{(\lambda)}(a+b) \geq v_n^{(\lambda)}(a) + v_m^{(\lambda)}(b) \quad (n, m \in \mathbb{N}; a, b \in \mathbb{R}). \quad (4)$$

Proof. Since $|H_{n+m} - (a+b)| \leq |H_n - b| + |(H_{n+m} - H_n) - a|$ we have

$$\begin{aligned} V_{n+m}^{(\lambda)}(x, a+b; \eta) &\geq \log \mathbf{P}^x \left(e^{-\lambda |H_n - b|} e^{-\lambda |(H_{n+m} - H_n) - a|} \right) \\ &= \log \mathbf{P}^x \left(e^{-\lambda |H_n - b|} e^{V_m^{(\lambda)}(0, a; \tau_{n, S_n} \circ \eta)} \right) \\ &= \log \sum_y \mathbf{P}^x \left(e^{-\lambda |H_n - b|} \mathbf{1}_{(S_n=y)} \right) e^{V_m^{(\lambda)}(0, a; \tau_{n,y} \circ \eta)} \\ &= V_n^{(\lambda)}(x, b; \eta) + \log \left(\sum_y \sigma_n(y) e^{V_m^{(\lambda)}(0, a; \tau_{n,y} \circ \eta)} \right) \\ &\geq V_n^{(\lambda)}(x, b; \eta) + \sum_y \sigma_n(y) V_m^{(\lambda)}(0, a; \tau_{n,y} \circ \eta) \quad (\text{Jensen's inequality}), \end{aligned}$$

with σ_n the probability measure on \mathbb{Z}^d :

$$\sigma_n(y) = \frac{1}{V_n^{(\lambda)}(x, b; \eta)} \mathbf{P}^x \left(e^{-\lambda |H_n - b|} \mathbf{1}_{(S_n=y)} \right) \quad (y \in \mathbb{Z}^d).$$

Observe that the random variables $\sigma_n(y)$ are measurable with respect to the sigma field $\mathcal{G}_n = \sigma(\eta(i, x) : i \leq n, x \in \mathbb{Z}^d)$, whereas the random variables $V_m^{(\lambda)}(0, a; \tau_{n,y} \circ \eta)$ are independent from \mathcal{G}_n . Hence, by stationarity,

$$\begin{aligned}
v_{n+m}^{(\lambda)}(a+b) &= \mathbf{Q}\left(V_{n+m}^{(\lambda)}(0, a+b; \eta)\right) \\
&\geq v_n^{(\lambda)}(b) + \sum_y \mathbf{Q}(\sigma_n(y)) \mathbf{Q}\left(V_m^{(\lambda)}(0, a; \tau_{n,y} \circ \eta)\right) \\
&= v_n^{(\lambda)}(b) + \sum_y \mathbf{Q}(\sigma_n(y)) v_m^{(\lambda)}(a) \\
&= v_n^{(\lambda)}(b) + v_m^{(\lambda)}(a) \mathbf{Q}\left(\sum_y \sigma_n(y)\right) \\
&= v_n^{(\lambda)}(b) + v_m^{(\lambda)}(a).
\end{aligned}$$

□

Step 2 There exists a function $I^{(\lambda)} : \mathbb{R} \rightarrow \mathbb{R}^+$ convex, non negative, Lipschitz with constant λ , such that

$$-\lim_{n \rightarrow \infty} \frac{1}{n} v_n^{(\lambda)}(a_n) = I^{(\lambda)}(\xi) \quad (\text{if } \frac{a_n}{n} \rightarrow \xi \in \mathbb{R}). \quad (5)$$

Proof. From $|H_n - a| \leq |H_n - b| + |a - b|$ we infer that

$$V_n^{(\lambda)}(0, a; \eta) \geq V_n^{(\lambda)}(0, b; \eta) - \lambda|a - b|.$$

Therefore the functions $v_n^{(\lambda)}$ are all Lipschitz continuous with the same constant λ and we combine this fact with standard subadditivity arguments (see e.g. Varadhan [13] or Alexander [1]). For sake of completeness, we give a detailed proof in the Appendix Lemma 4. □

Step 3 \mathbf{Q} almost surely, for any $\xi \in \mathbb{R}$, if $\frac{a_n}{n} \rightarrow \xi$, then

$$\lim_{n \rightarrow \infty} -\frac{1}{n} \log \mathbf{P}\left(e^{-\lambda|H_n - a_n|}\right) = I^{(\lambda)}(\xi). \quad (6)$$

Proof. Since the functions are Lipschitz, it is enough to prove that for any fixed $\xi \in \mathbb{Q}$, (6) holds a.s. This is where we use the restrictive assumptions made on the distribution of the environment. If the distribution of η is with bounded support, or Gaussian, or more generally satisfies a logarithmic Sobolev inequality with constant $c > 0$, then it has the Gaussian

concentration of measure property (see [2]): for any 1-Lipschitz function F of independent random variables distributed as η ,

$$\mathbf{P}(|F - \mathbf{P}(F)| \geq r) \leq 2e^{-r^2/c} \quad (r > 0).$$

It is easy to prove, as in Proposition 1.4 of [4], that the function

$$(\eta(k, x), k \leq n, |x| \leq n) \rightarrow \log \mathbf{P} \left(e^{-\lambda|H_n(\omega, \eta) - a|} \right)$$

is Lipschitz, with respect to the Euclidean norm, with Lipschitz constant at most $\lambda\sqrt{n}$. Therefore, the Gaussian concentration of measure yields

$$\mathbf{Q} \left(\left| V_n^{(\lambda)}(0, a; \eta) - v_n^{(\lambda)}(a) \right| \geq u \right) \leq 2e^{-\frac{\lambda^2 u^2}{cn}}.$$

We conclude by a Borel Cantelli argument combined with (5)

□

Observe that for fixed $\xi \in \mathbb{R}$, the function $\lambda \rightarrow I^{(\lambda)}(\xi)$ is increasing ; we shall consider the limit:

$$I(\xi) = \lim_{\lambda \uparrow +\infty} \uparrow I^{(\lambda)}(\xi)$$

which is by construction non negative, convex and lower semi continuous.

Step 4 The function I satisfy (2) and (3).

Proof. Given, $\xi \in \mathbb{R}$ and $\lambda > 0, \delta > 0$, we have

$$\mathbf{P} \left(\left| \frac{H_n}{n}(\omega, \eta) - \xi \right| \leq \delta \right) = \mathbf{P} \left(e^{-\lambda n \left| \frac{H_n}{n}(\omega, \eta) - \xi \right|} \geq e^{-\lambda n \delta} \right) \leq e^{\lambda n \delta} \mathbf{P} \left(e^{-\lambda |H_n - n\xi|} \right).$$

Therefore,

$$\begin{aligned} \limsup \frac{1}{n} \log \nu_n([\xi - \delta, \xi + \delta]) &\leq \lambda \delta - I^{(\lambda)}(\xi) \\ \limsup_{\delta \rightarrow 0} \limsup \frac{1}{n} \log \nu_n([\xi - \delta, \xi + \delta]) &\leq -I^{(\lambda)}(\xi) \end{aligned}$$

and we obtain by letting $\lambda \rightarrow +\infty$,

$$\limsup_{\delta \rightarrow 0} \limsup \frac{1}{n} \log \nu_n([\xi - \delta, \xi + \delta]) \leq -I(\xi).$$

Given $\xi \in \mathbb{R}$ such that $I(\xi) < +\infty$, and $\delta > 0$, we have for $\lambda > 0$,

$$\mathbf{P} \left(\left| \frac{H_n}{n} - \xi \right| < \delta \right) \geq \mathbf{P} \left(e^{-\lambda|H_n - n\xi|} - e^{-\lambda\delta n} \right).$$

Hence, if we choose $\lambda > 0$ large enough such that $\lambda\delta > I(\xi) \geq I^{(\lambda)}(\xi)$, we obtain

$$\liminf_{n \rightarrow +\infty} \frac{1}{n} \log \nu_n((\xi - \delta, \xi + \delta)) \geq -I^{(\lambda)}(\xi) \geq -I(\xi)$$

and therefore

$$\liminf_{\delta \rightarrow 0} \liminf_{n \rightarrow +\infty} \frac{1}{n} \log \nu_n((\xi - \delta, \xi + \delta)) \geq -I(\xi).$$

□

Appendix

Exponential tightness plays the same role in Large Deviations theory as tightness in weak convergence theory ; in particular it implies that the Large Deviations Property holds along a subsequence with a good rate function (see Theorem 3.7 of Feng and Kurtz [11], or Lemma 4.1.23 of Dembo and Zeitouni [10]). Therefore, once exponential tightness is established, we only need to identify the rate function : the Weak Large Deviations Property implies the Large Deviations Property with a good rate function (see Dembo and Zeitouni [10], Lemma 1.2.18). Our strategy of proof is then clear. First we establish exponential tightness, by applying the following Lemma to the probability ν_n and the Lyapunov function $x \rightarrow |x|$, then we prove a Weak Large Deviations Property by checking that the limits (2) and (3) hold.

Lemma 3. *Let $(\mu_n)_{n \in \mathbb{N}}$ be a sequence of probability measures on a Polish space X . Assume that there exists a (Lyapunov) function $F : X \rightarrow \mathbb{R}_+$ such that the level sets $\{F \leq C\}_{C > 0}$ are compacts, and*

$$\limsup_{n \rightarrow +\infty} \frac{1}{n} \log \left(\int e^{nF(x)} d\mu_n(x) \right) < +\infty.$$

The $(\mu_n)_{n \in \mathbb{N}}$ is exponentially tight, i.e. for each $A > 0$, there exists a compact K_A such that:

$$\limsup_{n \rightarrow +\infty} \log \mu_n(K_A^C) \leq -A.$$

Proof. Let $M = \limsup_{n \rightarrow +\infty} \frac{1}{n} \log \left(\int e^{nF(x)} d\mu_n(x) \right)$. There exists n_0 such that for $n \geq n_0$,

$$\frac{1}{n} \log \left(\int e^{nF(x)} d\mu_n(x) \right) \leq 2M.$$

Thanks to Markov inequality, for $C > 0$ and $n \geq n_0$,

$$\mu_n(F > C) = \mu_n(e^{nF} > e^{nC}) \leq e^{-nC} \int e^{nF} d\mu_n \leq e^{-n(C-2M)}.$$

Hence, if $C > 2M + A$, then for the compact set $K_A = \{F \leq C\}$, and $n \geq n_0$,

$$\frac{1}{n} \log \mu_n(K_A^C) \leq -(C - 2M) < -A.$$

□

In Step 2 of the proof of the main theorem, we apply the following Lemma to the family of functions $u_n = -v_n^{(\lambda)}$.

Lemma 4. *Assume that the non negative functions $u_n : \mathbb{R} \rightarrow \mathbb{R}_+$ are Lipschitz with the same constant $C > 0$, that is*

$$\forall n, x, y, \quad |u_n(x) - u_n(y)| \leq C|x - y|.$$

Assume furthermore the subadditivity:

$$\forall x, y, n, m, \quad u_{n+m}(x+y) \leq u_n(x) + u_m(y).$$

Then there exists a non negative function $I : \mathbb{R} \rightarrow \mathbb{R}_+$, Lipschitz with constant C , that satisfies:

(i) *if $\frac{a_n}{n} \rightarrow x$, then $\frac{1}{n} u_n(a_n) \rightarrow I(x)$.*

(ii) *I is convex.*

Proof. For fixed $x \in \mathbb{R}$, the sequence $z_n = u_n(nx)$ is subadditive and non negative:

$$z_{n+m} \leq z_n + z_m.$$

Therefore, by the standard subadditive theorem for sequences of real numbers, we can consider the limit

$$I(x) = \inf_{n \geq 1} \frac{1}{n} z_n = \lim_{n \rightarrow +\infty} \frac{1}{n} z_n = \lim_{n \rightarrow +\infty} \frac{1}{n} u_n(nx).$$

If we take limits in the inequality

$$\left| \frac{1}{n}u_n(nx) - \frac{1}{n}u_n(ny) \right| \leq C|x - y|$$

we obtain $|I(x) - I(y)| \leq C|x - y|$.

(i) Assume $\frac{a_n}{n} \rightarrow x$, then

$$\left| \frac{1}{n}u_n(nx) - \frac{1}{n}u_n(a_n) \right| \leq C \left| x - \frac{a_n}{n} \right| \rightarrow 0.$$

Hence, $\frac{1}{n}u_n(a_n) \rightarrow I(x)$.

(ii) We have, $\lfloor y \rfloor$ denoting the integer part of the real number y , for any x, y and $0 < t < 1$,

$$u_{\lfloor tn \rfloor + \lfloor (1-t)n \rfloor}(ntx + n(1-t)y) \leq u_{\lfloor tn \rfloor}(ntx) + u_{\lfloor (1-t)n \rfloor}(n(1-t)y).$$

Since $\frac{1}{n}(\lfloor tn \rfloor + \lfloor (1-t)n \rfloor) \rightarrow 1$, we have by (i)

$$\frac{1}{n}u_{\lfloor tn \rfloor + \lfloor (1-t)n \rfloor}(ntx + n(1-t)y) \rightarrow I(tx + (1-t)y).$$

Furthermore, since $\frac{1}{n}\lfloor tn \rfloor \rightarrow t$, we have by (i),

$$\frac{1}{n}u_{\lfloor tn \rfloor}(ntx) \rightarrow tI(x)$$

and similarly,

$$\frac{1}{n}u_{\lfloor (1-t)n \rfloor}(n(1-t)y) \rightarrow (1-t)I(y)$$

Combining these limits with the preceding inequality yields,

$$I(tx + (1-t)y) \leq tI(x) + (1-t)I(y)$$

that is I is convex. □

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