

First passage percolation on a hyperbolic graph admits bi-infinite geodesics*

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Abstract

Given an infinite connected graph, a way to randomly perturb its metric is to assign random i.i.d. lengths to the edges. An open question attributed to Furstenberg ([14]) is whether there exists a bi-infinite geodesic in first passage percolation on the euclidean lattice of dimension at least 2. Although the answer is generally conjectured to be negative, we give a positive answer for graphs satisfying some negative curvature assumption. Assuming only strict positivity and finite expectation of the random lengths, we prove that if a graph X has bounded degree and contains a Morse geodesic (e.g. is non-elementary Gromov hyperbolic), then almost surely, there exists a bi-infinite geodesic in first passage percolation on X .

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1 Introduction

First passage percolation is a model of random perturbation of a given geometry. In this paper, we shall restrict to the simplest model, where random i.i.d lengths are assigned to the edges of a fixed graph. We refer to [4, 12, 14] for background and references.

Let us briefly recall how FPP is defined. We consider a connected non-oriented graph X , whose set of vertices (resp. edges) is denoted by V (resp. E). For every function $\omega : E \rightarrow (0, \infty)$, we equip V with the weighted graph metric d_ω , where each edge e has weight $\omega(e)$. In other words, for every $v_1, v_2 \in V$, $d_\omega(v_1, v_2)$ is defined as the infimum over all path $\gamma = (e_1, \dots, e_m)$ joining v_1 to v_2 of $|\gamma|_\omega := \sum_{i=1}^m \omega(e_i)$. Observe that the graph metric on V corresponds to the case where ω is constant equal to 1, we shall simply denote it by d . We will now consider a probability measure on the set of all weight functions ω . We let ν be a probability measure supported on $[0, \infty)$. Our model consists in choosing independently at random the weights $\omega(e)$ according to ν . More formally, we equip the space $\Omega = [0, \infty)^E$ with the product probability that we denote by P .

A famous open problem in percolation theory is whether with positive probability, first passage percolation on \mathbb{Z}^2 admits a bi-infinite geodesic. In his Saint-Flour course from 84', Kesten attributes this question to Furstenberg (see [14]). Licea and Newman

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[15] made partial progress on this problem, which is still open, and mentioned that the conjecture that there are no such geodesics arose independently in the physics community studying spin glass. Wehr and Woo [16] proved absence of two sided infinite geodesic in a half plane, assuming the lengths distribution is continuously distributed with a finite mean.

For Riemannian manifolds, the existence of bi-infinite geodesics is influenced by the curvature of the space. It is well-known that complete simply connected non-positively curved Riemannian manifolds (such as the Euclidean space \mathbb{R}^n or the hyperbolic space \mathbb{H}^n) admit bi-infinite geodesics. Therefore, simply connected manifolds without two-sided geodesics must have positively curved regions. It is easy to come up with examples of complete Riemannian surfaces with bubble-like structures that create short cuts avoiding larger and larger balls around some origin. See [5] for background.

To help the reader's intuition, let us roughly describe a similar example in the graph setting. Starting with the standard Cayley graph of \mathbb{Z}^2 , it is not difficult to choose edges lengths among the two possible values $1/10$ and 1 , such that the resulting weighted graph has no bi-infinite geodesics. To do so, consider a sequence of squares C_n centered at the origin, whose size grows faster than any exponential sequence (e.g. like n^n). Then attribute length $1/10$ to the edges along C_n for all n , and 1 to all other edges. This creates large "bubbles" with relatively small neck in the graph (which in a sense can be interpreted as large positively curved regions). One easily checks for all n , for every pair of points at large enough distance from the origin, any geodesic between them never enters C_n (as it is more efficient to go around the shorter edges of its boundary, than traveling inside it). Random triangulations admit bubbles and indeed no two sided infinite geodesics. Geodesics go via "mountain passes" these are random analogues of the Morse geodesics defined below. See [10] for the study of FPP on random triangulations.

The Euclidean plane being flat, its discrete counterpart \mathbb{Z}^2 (and more generally \mathbb{Z}^d for $d \geq 2$) is in some sense at criticality for the question of existence of bi-infinite geodesics in FPP. Therefore, one should expect that in presence of negative curvature, FPP a.s. exhibits bi-infinite geodesics. For instance, this should apply to FPP on Cayley graphs of groups acting properly cocompactly by isometries on the hyperbolic space \mathbb{H}^d . We will see that this is indeed the case.

Let us first introduce some notation. Let X be a simple graph, with no double edges. Recall that a path $\gamma = (e_1, \dots, e_n)$ between two vertices x, y is a sequence of consecutive edges joining x to y . We denote $(x = \gamma(0), \dots, \gamma(n) = y)$ the set of vertices such that for all $0 \leq i < n$, $\gamma(i)$ and $\gamma(i + 1)$ are joined by the edge e_{i+1} . For all $i < j$, we shall also denote by $\gamma([i, j])$ the subpath (e_{i+1}, \dots, e_j) joining $\gamma(i)$ to $\gamma(j)$. Similarly, we define infinite paths indexed by \mathbb{N} (resp. bi-infinite paths indexed by \mathbb{Z}).

Definition 1.1. Let X be an infinite connected graph, and let $C \geq 1$ and $K \geq 0$. A path γ of length n between two vertices x and y is called a (C, K) -quasi-geodesic finite path if for all $0 < i < j \leq n$,

$$j - i (= |\gamma[i, j]|) \leq Cd(\gamma(i), \gamma(j)) + K.$$

Similarly, we define (C, K) -quasi-geodesic infinite (or bi-infinite) paths. An infinite (or a bi-infinite) path will simply be called a quasi-geodesic if it is (C, K) -quasi-geodesic for some constants C and K .

Definition 1.2. A bi-infinite path γ in X is called a *Morse quasi-geodesic* (resp. Morse geodesic) if it is a quasi-geodesic (resp. a geodesic) and if it satisfies the so-called Morse property: for all $C \geq 1$ and $K > 0$, there exists R such that every (C, K) -quasi-geodesic joining two points of γ remains inside the R -neighborhood of γ .

Remark 1.3. It is well-known and easy to deduce from its definition that in a locally finite weighted graph, whose weights are bounded away from 0, a Morse quasi-geodesic always lies at a bounded distance from a (Morse) bi-infinite geodesic. For the sake of completeness, let us outline the argument: let γ be a Morse quasi-geodesic, and let u_n and v_n be two sequences of vertices on γ escaping to infinity in opposite directions. For every n , let γ_n be a geodesic segment joining u_n to v_n . By the Morse property, γ_n remains at uniformly bounded distance from γ . On the other hand, the condition on the degree and on the weights ensure that any ball of finite radius in X is finite. Hence one can extract a sequence γ_{i_n} that converges to some bi-infinite geodesic γ_0 .

Theorem 1.4. Let X be an infinite connected graph with bounded degree, that contains a Morse quasi-geodesic γ . Assume $\mathbb{E}\omega_e < \infty$ and $\nu(\{0\}) = 0$. Then for a.e. ω , X_ω admits a bi-infinite geodesic. Moreover for every sequence of pairs of vertices (x_n, y_n) going to infinity on opposite sides of γ , for a.e. ω there exists a finite subset $A \subset X$ such that the ω -geodesic between x_n and y_n crosses A .

That is, if the underlying graph admits a two sided infinite Morse geodesic in the graph metric, then the random FPP metric will have a two sided infinite geodesic a.s.

Very recently Ahlberg and Hoffman [2] made substantial progress on the structure of geodesic rays for FPP on \mathbb{Z}^2 solving the midpoint problem (from [6]) which is related to the non existence of bi-infinite geodesic. They showed that the probability a shortest path between $(-n, 0)$ and $(n, 0)$ will go via $(0, 0)$ is going to 0 with n . Their upper bound on the probability is going very slowly to 0, and is likely far from the truth. The theorem above shows that the probability of the midpoint event is not going to 0 in the distance, along a Morse geodesic. This can be useful in proving linear variance, see the conjecture at the end.

We briefly recall the definition of a hyperbolic graph. A geodesic triangle in a graph X consists of a triplet of vertices $x_0, x_1, x_2 \in V$, and of geodesic paths $\gamma_0, \gamma_1, \gamma_2$ such that γ_i joins x_{i+1} to x_{i+2} where $i \in \mathbb{Z}/3\mathbb{Z}$. Given $\delta \geq 0$, a geodesic triangle is called δ -thin if for every $i \in \mathbb{Z}/3\mathbb{Z}$, every vertex v_i on γ_i lies at distance at most δ from either γ_{i+1} or γ_{i+2} . Said informally, a geodesic triangle is δ -thin if every side is contained in the δ -neighborhood of the other two sides. A graph is hyperbolic if there is $\delta < \infty$ so that all geodesic triangles are δ -thin. It is well-known [13] that in a hyperbolic graph, any bi-infinite quasi-geodesic is Morse. In particular, we deduce the following

Corollary 1.5. Let X be a hyperbolic graph with bounded degree containing at least one bi-infinite geodesic. Assume $\mathbb{E}\omega_e < \infty$ and $\nu(\{0\}) = 0$. Then for a.e. ω , X_ω admits a bi-infinite geodesic. Moreover for every sequence of pairs of vertices (x_n, y_n) going to infinity on opposite sides of a fixed quasi-geodesic in the graph metric of X , for a.e. ω there exists a finite subset $A \subset X$ such that the ω -geodesic between x_n and y_n crosses A .

Note that the case where ν is supported in an interval $[a, b] \subset (0, \infty)$ is essentially obvious. Indeed, for all ω , the weighed graph X_ω is bi-Lipschitz equivalent to X . We deduce that a Morse quasi-geodesic in X remains a Morse quasi-geodesic in X_ω (adapting the definition to weighted graphs), and therefore lies at bounded distance from an actual bi-infinite geodesic.

We finish this introduction mentioning that Theorem 1.4 applies to a wide class of Cayley graphs, including Cayley graphs of relatively hyperbolic groups, Mapping Class groups, and so on.

2 Preliminary lemmas

We start with a useful characterization of Morse quasi-geodesics, that one may take as a definition.

Proposition 2.1. [11, Proposition 3.24 (3)] A bi-infinite quasi-geodesic γ_0 is Morse if and only if the following holds. For every $C \geq 1$, there exists $D \geq 0$ such that every path of length $\leq Cn$ connecting two points x, y on γ at distance $\geq n$ crosses the D -neighborhood of the middle third of the segment of γ_0 joining x to y .

We deduce the following criterion, which we shall use in the sequel.

Lemma 2.2. Let X be an infinite connected graph with bounded degree. Assume γ_0 is a Morse quasi-geodesic. Then there exists an increasing function $\phi : \mathbb{R}_+ \rightarrow \mathbb{R}_+$ such that $\lim_{t \rightarrow \infty} \phi(t) = \infty$, and with the following property. Assume

- x, y belong to γ_0 ;
- x' and y' are vertices such that $d(x, x') = d(y, y') = R$, and $d(x', y') \geq 10R$;
- γ is a path joining x' to y' , and remains outside of the R -neighborhood of γ_0 .

Then

$$|\gamma| \geq \phi(R)d(x, y).$$

Proof. Assume by contradiction that there exists a constant $C > 0$, and for every n , an integer $R \geq n$, vertices x, x', y, y' and a path γ of length $\leq Cd(x, y)$ such that $d(x, x') = d(y, y') = R$, $d(x', y') \geq 10R$, and γ avoids the R -neighborhood of γ_0 . By choosing n large enough, we can assume that $R > D$. Applying Proposition 2.1 to the path obtained by concatenating γ with geodesics from x' to x and from y' to y yields the desired contradiction. \square

The hypothesis $E\omega_e < \infty$ is used (only) in the following trivial lemma.

Lemma 2.3. Let X be a connected graph, and let γ be a self avoiding path. Assume $0 < b = \mathbb{E}\omega_e < \infty$. Then for a.e. ω , there exists $r_0 = r_0(\omega)$ such that for all $i \leq 0 \leq j$,

$$|\gamma([i, j])|_\omega \leq 2b(j - i) + r_0.$$

Proof. This immediately follows from the law of large number, using that the edges length distributions are i.i.d. \square

Our assumption $\nu(\{0\}) = 0$ is used to prove the following two lemmas.

Lemma 2.4. Let X be an infinite connected graph with bounded degree and assume that $\nu(\{0\}) = 0$. There exists an increasing function $\alpha : (0, \infty) \rightarrow (0, 1]$ such that $\lim_{t \rightarrow 0} \alpha(t) = 0$, and such that for all finite path γ and all $\varepsilon > 0$,

$$P(|\gamma|_\omega \leq \varepsilon|\gamma|) \leq \alpha(\varepsilon)^{|\gamma|}.$$

Proof. The assumption implies that for all $\lambda > 0$, there exists $\delta > 0$ such that $\nu([0, 0+\delta]) < \lambda$. Let γ be a path of length n . Assume that $|\gamma|_\omega \leq \varepsilon|\gamma|$, and let N be the number of edges of γ with ω -length $\geq \delta$. It follows that

$$\delta N \leq \varepsilon n,$$

so we deduce that $N \leq \varepsilon n / \delta$. This imposes that at least $(1 - \varepsilon/\delta)n$ edges of γ have ω -length $\leq \delta$. Recall that by Stirling's formula, given some $0 < \alpha < 1$, the number of ways to choose αn edges in a path of length n is

$$\sim \frac{n^n}{(\alpha n)^{\alpha n} ((1 - \alpha)n)^{(1 - \alpha)n}} = (1/\alpha)^{\alpha n} (1/(1 - \alpha))^{(1 - \alpha)n}.$$

Thus the probability that γ has ω -length at most εn is less than a universal constant times

$$\frac{\lambda^{(1-\varepsilon/\delta)n}}{(\varepsilon/\delta)^{(\varepsilon/\delta)n}(1-\varepsilon/\delta)^{(1-\varepsilon/\delta)n}} = \left(\frac{\lambda^{1-\varepsilon/\delta}}{(\varepsilon/\delta)^{\varepsilon/\delta}(1-\varepsilon/\delta)^{1-\varepsilon/\delta}} \right)^n.$$

Note that

$$\lim_{\varepsilon \rightarrow 0} \frac{\lambda^{1-\varepsilon/\delta}}{(\varepsilon/\delta)^{\varepsilon/\delta}(1-\varepsilon/\delta)^{1-\varepsilon/\delta}} = \lambda.$$

In other words, we have proved that for all $\lambda > 0$, there exists $\varepsilon > 0$ such that

$$P(|\gamma|_\omega \leq \varepsilon|\gamma|) \leq (2\lambda)^{|\gamma|}$$

which is equivalent to the statement of the lemma. □

Lemma 2.5. Let X be an infinite connected graph with bounded degree, and let o be some vertex of X . Assume $\nu(\{0\}) = 0$. Then there exists $c > 0$ such that for a.e. ω , there exists $r_1 = r_1(\omega)$ such that for all finite path γ such that¹ $d(\gamma, o) \leq |\gamma|$, one has

$$|\gamma|_\omega \geq c|\gamma| - r_1.$$

Proof. Let q be an upper bound on the degree of X , and let $n \geq 1$ be some integer. Every path of length n lying at distance at most n from o is such that $d(o, \gamma(0)) \leq 2n$, hence such a path is determined by a vertex in the ball $B(o, 2n)$, whose size is at most $q^{2n} + 1$, and a path of length n originated from this vertex. Therefore the number of such paths is at most $(q + 1)^{3n}$.

On the other hand, we deduce from the previous lemma that for $c > 0$ small enough, the probability that there exists some path γ of length n , and at distance at most n from o , and satisfying $|\gamma|_\omega \leq c|\gamma|$ is less than $1/(q + 1)^{4n}$. Hence the lemma follows by Borel-Cantelli. □

3 Proof of Theorem 1.4

Let γ_0 be some Morse quasi-geodesic. By Remark 1.3, we do not loose generality by assuming that our Morse quasi-geodesic γ_0 is a bi-infinite geodesic of the graph X . We let $o = \gamma_0(0)$ be some vertex. We consider two sequences of vertices (x_n) and (y_n) on γ_0 escaping to infinity in opposite directions.

We let $\Omega' \subset \Omega$ be a measurable subset of full measure such that the conclusions of Lemmas 2.3 and 2.5 hold. For all n and for all ω , we pick measurably an ω -geodesic γ_ω^n between x_n and y_n . Note that Lemmas 2.3 and 2.5 imply that such a geodesic exists: by Lemma 2.3, we have that $d_\omega(x_n, y_n)$ is finite, and by Lemma 2.5, paths of length $\geq M$ have ω -length going to infinity as $M \rightarrow \infty$.

If we can prove the second part of Theorem 1.4, i.e. that for all $\omega \in \Omega'$, there exists a constant $R_\omega > 0$ such that for all n , $d(\gamma_\omega^n, o) \leq R_\omega$, then the first part of Theorem 1.4 follows by a straightforward compactness argument². So we shall assume by contradiction that for some $\omega \in \Omega'$, there exists a sequence R_n going to infinity such that γ_ω^n avoids $B(o, 100R_n)$.

Lemma 3.1. Assuming the above, there exist integers $q < p$ such that

$$d(\gamma_\omega^n(p), \gamma_0) = d(\gamma_\omega^n(q), \gamma_0) = R_n,$$

¹Here $d(\gamma, o)$ denotes the distance between o and the set of vertices $\{\gamma(0), \gamma(1), \dots\}$.

²Indeed, observe that Lemma 2.5 implies that X_ω is a.e. locally finite in the sense that d_ω -bounded subsets of vertices are finite.

and such that for all $p \leq k \leq q$,

$$d(\gamma_\omega^n(k), \gamma_0) \geq R_n,$$

and

$$d(\gamma_\omega^n(p), \gamma_\omega^n(q)) \geq 10R_n.$$

Proof. (Note that this is obvious from a picture). Let $\gamma_0(i)$ and $\gamma_0(j)$ with $i < 0 < j$ be the two points at distance $100R_n$ from $o = \gamma_0(0)$. Since γ_0 is a geodesic, $\gamma_0((-\infty, i])$ and $\gamma_0([j, \infty))$ are distance $200R_n$ from one another. Let r be the first time integer such that $d(\gamma_\omega^n(r), \gamma_0([j, \infty))) = 100R_n$. By triangular inequality, $d(\gamma_\omega^n(r), \gamma_0((-\infty, i])) \geq 100R_n$, and since we also have $d(\gamma_\omega^n(r), o) \geq 100R_n$, we deduce that

$$d(\gamma_\omega^n(r), \gamma_0) \geq 50R_n.$$

We let p and q be respectively the largest integer $\leq r$ and the smallest integer $\geq r$ such that

$$d(\gamma_\omega^n(p), \gamma_0) = d(\gamma_\omega^n(q), \gamma_0) = R_n.$$

Clearly, for all $p \leq k \leq q$,

$$d(\gamma_\omega^n(k), \gamma_0) \geq R_n.$$

Moreover, recall that γ_ω^n avoids $B(o, 100R_n)$. Hence if x and y are points on γ_0 such that $d(\gamma_\omega^n(p), x) = d(\gamma_\omega^n(q), y) = R_n$, we deduce by triangular inequality that $d(x, o) \geq 99R_n$ and $d(y, o) \geq 99R_n$. But since x and y lie on both sides of o , this implies that $d(x, y) \geq 198R_n$ (because γ_0 is a geodesic). Now by triangular inequality, we conclude that

$$d(\gamma_\omega^n(p), \gamma_\omega^n(q)) \geq d(x, y) - 2R_n \geq 196R_n \geq 10R_n.$$

So the lemma follows. □

End of the proof of Theorem 1.4

We now let i and j be integers such that

$$d(\gamma_\omega^n(p), \gamma_0(i)) = d(\gamma_\omega^n(q), \gamma_0(j)) = R_n.$$

Note that by triangular inequality, $j - i = |\gamma_0([i, j])| \geq R_n$.

By Lemmas 2.5 and 2.2, we have

$$\begin{aligned} |\gamma_\omega^n([p, q])|_\omega &\geq c|\gamma_\omega^n([p, q])| - r_1 \\ &\geq c\phi(R_n)|\gamma_0([i, j])| - r_1 \\ &= c\phi(R_n)(j - i) - r_1. \end{aligned}$$

On the other hand, since γ_ω^n is an ω -geodesic between x_n and y_n , we have

$$\begin{aligned} |\gamma_\omega^n([p, q])|_\omega &\leq 2R_n + |\gamma_0([i, j])|_\omega \\ &\leq 2R_n + 2b|\gamma_0([i, j])| + r_0 \\ &= 2R_n + 2b(j - i) + r_0, \end{aligned}$$

where the second inequality follows from Lemma 2.3.

Gathering these inequalities, we obtain (for n large enough)

$$(c\phi(R_n) - 2b)R_n \leq (c\phi(R_n) - 2b)(j - i) \leq 2R_n + r_1 + r_0,$$

which yields a contradiction since $\phi(R_n) \rightarrow \infty$ as $n \rightarrow \infty$. This ends the proof of Theorem 1.4.

4 Remarks and questions

- (Cayley graphs) We do not know a single example of an infinite Cayley graph, for which FPP a.s. admits no bi-infinite geodesics (to fix the ideas, assume the edge length distribution is supported on the interval $[1, 2]$).
- (Adding dependence) Given a hyperbolic Cayley graph, rather than considering independent edges lengths it is natural to consider other group invariant distributions. Under which natural conditions (mixing?) on this distribution do bi-infinite geodesics a.s. exist?
- (Poisson Voronoi and other random models) A variant of random metric perturbation is obtained via Poisson Voronoi tiling of a measure metric space. It seems likely that our method of proof applies to the hyperbolic Poisson Voronoi tiling, see [7]. Recently other versions of random hyperbolic triangulations were constructed, [3] [9]. Since those are not obtained by perturbing an underlying hyperbolic space, our proof does not apply to this setting.
- (Variance along Morse geodesics) We *conjecture* that under a suitable moment condition on the edge-length distribution, the variance of the random distance grows linearly along the Morse quasi-geodesic, unlike in Euclidean lattices [6]. For lengths which are bounded away from zero and infinity, Morse's property ensures that geodesics remain at uniformly bounded distance from γ , hence reducing the problem to "filiform graphs", i.e. graphs quasi-isometric to \mathbb{Z} . A (very) special class of filiform graphs is dealt with in [1] where a linear variance growth is proven.

References

- [1] D. Ahlberg. Asymptotics of first-passage percolation on 1-dimensional graphs. *Advances in Applied Probability*, **47** (2015), 182–209. MR-3327321
- [2] D. Ahlberg and C. Hoffman, Random coalescing geodesics in first-passage percolation. arXiv:1609.02447 (2016).
- [3] O. Angel and G. Ray. Classification of Half Planar Maps. *Ann. Probab.* **433** (2015), 1315–1349. MR-3342664
- [4] A. Auffinger, M. Damron and J. Hanson, 50 years of first passage percolation. arXiv:1511.03262
- [5] W. Ballmann, Lectures on spaces of nonpositive curvature. DMV Seminar 25, Basel: *Birkhauser Verlag*, pp. viii+112 (1995). MR-1377265
- [6] I. Benjamini, G. Kalai, O. Schramm. First passage percolation has sublinear distance variance. *Ann. Probab.* **31** (2003) 1970–1978. MR-2016607
- [7] I. Benjamini, E. Paquette and J. Pfeffer. Anchored expansion, speed, and the hyperbolic Poisson Voronoi tessellation. arXiv:1409.4312
- [8] J. T. Cox and R. Durrett. Some limit theorems for percolation processes with necessary and sufficient conditions. *Ann. Probab.* **9** (1981) 583–603.
- [9] N. Curien. Planar stochastic hyperbolic infinite triangulations. *Probab. Theory Relat. Fields* **1653** (2016), 509–540. MR-3520011
- [10] N. Curien and J-F. Le Gall, First-passage percolation and local modifications of distances in random triangulations. arXiv:1511.04264
- [11] C. Drutu, S. Mozes, M. Sapir. Divergence in lattices in semisimple Lie groups and graphs of groups. *Trans. Amer. Math. Soc.* **362** (2010), 2451–2505.
- [12] G. Grimmett and H. Kesten. Percolation since Saint-Flour. Percolation theory at Saint-Flour, Probab. St.-Flour, Springer, Heidelberg, (2012).
- [13] M. Gromov, Hyperbolic groups, "Essays in group theory", S. Gersten (ed), *MSRI Publ.* **8**, Springer (1987), 75–265.

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- [14] H. Kesten. Aspects of first passage percolation. École d'Été de probabilité de Saint-Flour XIV - 1984, Lecture Notes in Math., 1180, *Springer*, Berlin, (1986) 125–264.
- [15] C. Licea and C. Newman. Geodesics in two-dimensional first-passage percolation. *Ann. Probab.* **24** (1996) 399–410. MR-1387641
- [16] J. Wehr and J. Woo. Absence of geodesics in first-passage percolation on a half-plane. *Ann. Probab.* **26** (1998) 358–367.