The social network model on infinite graphs

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Abstract

Given an infinite connected regular graph $G = (V,E)$, place at each vertex Poisson($\lambda$) walkers performing independent lazy simple random walks on $G$ simultaneously. When two walkers visit the same vertex at the same time they are declared to be acquainted. We show that when $G$ is vertex-transitive and amenable, for all $\lambda > 0$ a.s. any pair of walkers will eventually have a path of acquaintances between them. In contrast, we show that when $G$ is non-amenable (not necessarily transitive) there is always a phase transition at some $\lambda_c(G) > 0$. We give general bounds on $\lambda_c(G)$ and study the case that $G$ is the $d$-regular tree in more detail. Finally, we show that in the non-amenable setup, for every $\lambda$ there exists a finite time $t_\lambda(G)$ such that a.s. there exists an infinite set of walkers having a path of acquaintances between them by time $t_\lambda(G)$.

Keywords: Social network, percolation, random walks, infinite cluster, amenability, phase transition.

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1 Introduction

We consider the following model for a social network which we call the social network model (SN as a shorthand). The model was proposed by Itai Benjamini and was first investigated in [4] in the context of finite graphs (see §1.2 for further details). In this work we study the model on infinite graphs. Let $G = (V,E)$ be an infinite connected $d$-regular graph, which is the underlying graph of the SN model. In our model we have walkers performing independent lazy simple random walks on $G$, denoted by LSRW (see §2 for a definition).

Let $t = \{t_i\}_{i \in \mathbb{Z}^+} \cup \{\infty\}$. We say that two walkers $w, w'$ have met by time $t$, which we denote by $w_t \leftrightarrow w'$, if there exists $t_0 \leq t$ such that they have the same position at time $t_0$. After two walkers meet they continue their walks independently without coalescing. We write $w \sim w'$ (“meeting by time $\infty$”), if there exists some finite $t$ such that $w_t \leftrightarrow w'$. “Meeting by time $t$” is a symmetric relation and thus induces a unique minimal equivalence relation that contains it. We call this equivalence relation having a path of acquaintances by time $t$ and denote it by $\sim_t$ (note that $w \sim w'$ iff there exists some finite $t$ such that $w \sim_t w'$).

Consequently, the SN model typically evolves much faster than such models.

We are interested in the coalescence process of the equivalence classes, and in particular in the number of equivalence classes of $\sim$ and in the existence of an infinite equivalence class of $\sim$ for some finite $t$.

Let $\mathcal{W} := \bigcup_{u \in V} \mathcal{W}_u$ be the set of all walkers. Denote by $\text{Con}$ (a shorthand for “connected”) the event that $w \sim w'$ for all $w, w' \in \mathcal{W}$ (i.e., $\text{Con}$ is the event that every pair of walkers eventually have a path of acquaintances between them). The following question was proposed to us by Itai Benjamini [2].

**Question 1.1.** Let $T_d$ be the infinite $d$-regular tree. Does $P_\lambda[\text{Con}] = 1$ for all $\lambda > 0$?

We give a negative answer to this question (Theorem 2). This raises the problem of identifying for which graphs $\text{Con}$ occurs $P_\lambda$-a.s. for all $\lambda > 0$.

**Definition 1.2** (Critical density). Let $G = (V,E)$ be an infinite connected regular graph. The critical density for the SN model on $G$ is defined to be

$$
\lambda_c(G) := \inf\{\lambda : \exists p > 0 \text{ such that } \inf_{u,v \in V} P_\lambda[u \sim v | \mathcal{W}_u \neq \emptyset, \mathcal{W}_v \neq \emptyset] > p\}.
$$
where for a pair of vertices $u, v$ and $t \in \mathbb{Z}_+ \cup \{\infty\}$ we write $u \xrightarrow{t} v$ (respectively, $u \leftrightarrow v$) if there exist some $w \in W_v$ and $w' \in W_u$ such that $w \xrightarrow{t} w'$ (respectively, $w \leftrightarrow w'$).

The following phase transition occurs around the critical density:

**Proposition 1.3.** Let $G$ be an infinite connected regular graph. Then

$$P_\lambda[\text{Con}] = \begin{cases} 0 & \text{if } 0 \leq \lambda < \lambda_c(G), \\ 1 & \text{if } \lambda > \lambda_c(G). \end{cases}$$  \hspace{1cm} (1.1)

A graph $G = (V, E)$ is called *vertex transitive* if the action of its automorphisms group, $\text{Aut}(G)$, on its vertices is transitive (i.e., $\{\varphi(v) : \varphi \in \text{Aut}(G)\} = V$ for all $v$). The spectral radius of a random walk on $G = (V, E)$ with transition matrix $P$ is $\rho := \limsup_n (P^n(v, u))^{1/n}$ (the limit is independent of $u, v \in V$). A graph $G$ is called *amenable* if $\rho = 1$ for LSRW on $G$ (otherwise, it is called *non-amenable*). We review some consequences of amenability/non-amenability in Sections 2.5 and 4.

There are numerous characterizations of amenability. Most characterizations describe a certain dichotomy between amenable graphs and non-amenable graphs. In particular, several probabilistic models exhibit very different behaviors in the amenable setup and the non-amenable setup. However, proving a sharp dichotomy may be an extremely challenging task for some models. For instance, it is a major open problem in percolation theory to establish that for vertex transitive graphs, the existence of a non-uniqueness regime for Bernoulli percolation is equivalent to non-amenability (for further details see [11, Chapter 7]). The following theorem asserts that for transitive graphs, amenability can be characterized by the SN model (note that there is no transitivity assumption in the non-amenable setup).

**Theorem 1.** For every infinite connected vertex transitive amenable graph of finite degree $\lambda_c = 0$. Conversely, for every infinite non-amenable connected regular graph $\lambda_c > 0$.

**Remark 1.4.** A similar dichotomy is believed to hold for the frog model (in the context of recurrence), however the only family of non-amenable graphs for which a phase transition is known to exist in the frog model is the infinite $d$-regular tree for all $d \geq 3$ [7]. The frog model in the amenable setup is studied in [13].

**Remark 1.5.** Using our analysis of the non-amenable setup it is not hard to verify that by attaching the root of an infinite binary tree to the origin of $\mathbb{Z}^d$ we obtain a non-transitive amenable graph with $\lambda_c > 0$. Thus the transitivity assumption is necessary in Theorem 1.

A question which arises naturally is what can be said about $\lambda_c$ in the non-amenable setup. We give general lower and upper bounds on $\lambda_c(G)$ (Theorems 8.1 and 5.1, respectively) in terms of the spectral radius of the walk $\rho$ and its degree $d$. It turns out that the holding probability (which obviously affects $\rho$) can drastically change $\lambda_c$, which is somewhat counter-intuitive at first sight. As an illustrating example we consider the infinite $d$-regular tree.
Theorem 2. Let $T_d = (V,E)$ be the infinite $d$-regular tree for some $d \geq 3$. There exist absolute constants $c,C > 0$ such that when the holding probability of the walks is taken to be $1/(d + 1)$ we have that
\[ c\sqrt{d} \leq \lambda_c(T_d) \leq C\sqrt{d}. \] (1.2)

In contrast, it follows from Theorem 5.1 that when the holding probability is taken to be $1/2$ we have that $\lambda_c(T_d) \leq C\log d$ (in fact, when the holding probability is $1/2$, one can refine Theorem 8.1 and obtain as a corollary that $\lambda_c(T_d) \geq c\log d$).

1.1 Infinite friend clusters in finite time

We now turn our attention to the problem of determining the existence of an infinite equivalence class of $\sim$ for some finite $t$. Let $t \in \mathbb{Z}_+ \cup \{\infty\}$. For each walker $w$ we call the set walkers in the same equivalence class of $\sim$ as $w$, the friend cluster of $w$ at time $t$ and denote it by $FC_t(w)$. When $t = \infty$ we call this set the friend cluster of $w$ and denote it by $FC(w) := FC_\infty(w)$. More generally, when $t = \infty$ we often omit it from our terminology and notation. Recall that for $u,v \in V$ and $t \in \mathbb{Z}_+ \cup \{\infty\}$ we denote $u \leftrightarrow v$ and $u \sim v$ iff there exist $w \in W_u$ and $w' \in W_v$ so that $w \leftrightarrow w'$ and $w \sim w'$, respectively. Let
\[ \Xi := \{u \in V : |W_u| > 0\} \]
be the set of initially occupied vertices. It will be convenient to define the friend cluster of a vertex $u$ at time $t$, which by abuse of notation we denote by $FC_t(u)$, which is defined as follows. If $u \in \Xi$ then we define $FC_t(u)$ to be the friend cluster of the walkers in $W_u$ at time $t$, i.e., $FC_t(u) := FC_t(w)$ for some $w \in W_u$. Otherwise, we set $FC_t(u)$ to be the empty-set. Let that
\[ \lambda_c(G) = \inf\{\lambda : \exists p > 0 \text{ such that } \forall u,v \in V, \ P_\lambda[FC(u) = FC(v) | u,v \in \Xi] \geq p\}. \] (1.3)

Minor adjustments to the analysis of the frog model on $(\mathbb{Z}/n\mathbb{Z})^d$ from [3] show that when the underlying graph is $\mathbb{Z}^d$ with $d > 1$, for every $\lambda > 0$ there is indeed an infinite friend cluster in finite time a.s..

Conjecture 1.6 (Benjamini [2]). Let $G$ be an infinite connected graph of bounded degree. Assume that for some $0 < p < 1$ bernoulli bond percolation on $G$ with survival probability $p$ has an infinite connected component with probability 1. Then for all $\lambda > 0$, there exists $t_\lambda(G) > 0$ such that
\[ \forall t > t_\lambda(G), \ P_\lambda[\max_{w} |FC_t(w)| = \infty] = 1. \]

The following theorem provides a partial answer.
Theorem 3. Let $G = (V, E)$ be a regular connected infinite non-amenable graph. Denote the spectral radius of LSRW with some arbitrary holding probability $0 \leq p < 1$ by $\rho$. Let $IC(t)$ be the event that $\max_{v \in V} |FC_t(v)| = \infty$. Then there exists an absolute constant $C > 0$ (independent also of $G$) such that for all $\lambda \in (0, 1)$ and $t \geq \lceil \frac{C}{\lambda(1-\rho)} \rceil =: t_{C, \lambda}$

$$P_\lambda[IC(t)] = 1.$$ 

Remark 1.7. Theorem 6 in [4] asserts that (for $\lambda = 1$) if $G$ is a $d$-regular expander of size $n$, then there exists some constants $t, c_1$ (depending only on the spectral gap of the walk on $G$ and on $d$) such that after $t$ steps $\max_v |FC(v)| \geq n/6$ with probability at least $1 - e^{-c_1 n}$. However, the techniques from the finite setup do not carry over to the infinite setup of Theorem 3.

1.2 Related work

The SN model, proposed by Itai Benjamini, was first investigated in the context of finite graphs and $\lambda = 1$ in [4], where it was shown that there exist constants $c, C_d > 0$ such that for every finite connected graph $G = (V, E)$ of maximal degree $d$,

$$P[c \log |V| \leq \inf \{t : FC_t(u) = FC_t(v) \text{ for all } u, v \in \Xi \} \leq C_d \log^3 |V|] \geq 1 - |V|^{-1}.$$ 

1.3 Organization of the paper

In §2 we present some preliminaries. In §3 we prove Proposition 1.3. In §4 we prove the assertion of Theorem 1 in the transitive amenable setup (namely, that $\lambda_c = 0$). In §5 we bound $\lambda_c$ from above in the non-amenable setup. In §6 we consider the $d$-ary try and prove Theorem 2. In §7 we prove Theorem 3. Finally, in §8 we conclude the proof of Theorem 1 by proving a general lower bound on $\lambda_c$ in the non-amenable setup.

2 Preliminaries and additional notation

LSRW is defined as follows. If a walker’s current position is $v$, then the walker either stays in its current position w.p. $1/2$, which we refer to as the holding probability, or moves to one of the neighbors of $v$ w.p. $1/(2d)$. We shall also consider the case of holding probability $1/(d + 1)$ in which $1/(2d)$ and $1/2$ above are both replaced by $1/(d + 1)$.

2.1 Reversibility, Poisson thinning, stationarity of the occupation measure and independence of the number of walkers performing different walks.

Let $G = (V, E)$ be a regular graph. Then the transition kernel $P$ of LSRW on $G$ is symmetric (i.e., $P(x, y) = P(y, x)$ for all $x, y \in V$) and so $P^t$ is also symmetric for all
Let $t \in \mathbb{N}$. In other words, $P$ is reversible w.r.t. the counting measure on $V$. We now establish a certain independence property for walks in $G$, which in particular implies stationarity of the occupation measure for the SN model.

A walk of length $k$ in $G$ is a sequence of $k + 1$ vertices $(v_0, v_1, \ldots, v_k)$ such that for all $0 \leq i < k$ either $v_i = v_{i+1}$ or $\{v_i, v_{i+1}\} \in E$. Let $\Gamma_k$ be the collection of all walks of length $k$ in $G$. Throughout, we denote the set of walkers whose initial position is in $v$ by $W_v := \{w^v_1, \ldots, w^v_{N_v}\}$. We denote by $w^v_i(t)$ the position of the walker $w^v_i$ at time $t$. We say that a walker $w^v_i$ performed a walk $\gamma \in \Gamma_k$ if $(w^v_i(0), \ldots, w^v_i(k)) = \gamma$. For a walk $\gamma = (\gamma(0), \ldots, \gamma(k)) \in \Gamma_k$ for some $k \geq 1$, we denote $p(\gamma) := \prod_{i=0}^{k-1} P(\gamma_i, \gamma_{i+1})$. This is precisely the probability that some given walker $w \in W_{\gamma(0)}$ performed the walk $\gamma$.

Let $\gamma_{\text{rev}}$ be the reversal of $\gamma \in \Gamma_k$. That is $\gamma_{\text{rev}}(i) = \gamma(k - i)$ for all $0 \leq i \leq k$. Then by reversibility $p(\gamma) = p(\gamma_{\text{rev}})$. We denote the number of walkers whose position at time $t$ is $v$ by $Y_v(t)$. By reversibility, for all $v \in V$ and $t > 0$ we have $\mathbb{E}_\lambda[Y_v(t)] = \sum_{u \in V} \mathbb{E}_\lambda[Y_u(0)]P^t(u, v) = \lambda \sum_{u \in V} P^t(v, u) = \lambda$. Thus by Poisson thinning:

**Fact 2.1.** Let $G = (V, E)$ be a regular graph. Denote the number of walkers who performed a walk $\gamma$ (in the above sense) by $X_\gamma$. For every $\lambda > 0$, under $P_\lambda$ we have that $X_\gamma \sim \text{Pois}(\lambda \rho(\gamma))$, for all $t > 0$ and $\gamma \in \Gamma_t$. Moreover, $(X_\gamma)_{\gamma \in \Gamma}$ are independent for each fixed $t > 0$. Consequently, $(Y_v(t))_{v \in V}$ are i.i.d. Pois($\lambda$) random variables for each fixed $t > 0$.

### 2.2 Further notation, monotonicity and the regeneration Lemma

Let $t \in \mathbb{Z} \cup \{\infty\}$. The acquaintances graph at time $t$, denoted by $AC_t(G) = (V, E_t)$, is a random graph in which two distinct vertices $u, v \in V$ are connected by an edge iff $u \leftrightarrow v$. We denote $AC(G) := AC_\infty(G)$. We denote the connected component of $v$ in $AC_t(G)$ by $C_t(v)$. Note that $C_t(v) = \bigcup_{u \in C_t(v)} W_u$, where as before $W_u$ is the set of walkers which initially occupy vertex $u$. When clear from context, we omit $G$ from the notation. When we want to emphasize the density of the walkers we write $AC_t^\lambda(G)$. We denote the collection of walkers which occupy vertex $v$ (respectively, the set $A \subseteq V$) at time $t$ by $W_v(t)$ (respectively, $W_A(t)$) and set $W_A := W_A(0) = \bigcup_{a \in A} W_a$ (this is the set of walkers whose initial position is in $A$).

**Proposition 2.2.** Let $G = (V, E)$ be a regular graph. There exists a probability space on which the SN model on $G$ is defined for all $\lambda > 0$ simultaneously, such that deterministically, for all $t \in \mathbb{Z} \cup \{\infty\}$ we have that $AC_t^{\lambda_1}$ is a subgraph of $AC_t^{\lambda_2}$ for all $\lambda_1 \leq \lambda_2$.

The construction is fairly straightforward and is very similar to the one in [3]. We present it in the Appendix 10 for the sake of completeness.

**Lemma 2.3.** (Regeneration Lemma) Let $G = (V, E)$ be an infinite $d$-regular graph. Let $Y_{v,B}(t)$ be the number of walkers belonging to $W_B$ which are at vertex $v$ at time $t$. Then for every finite set $A \subseteq V$ and each fixed $t$, $(Y_{v,A^c}(t))_{v \in V}$ are independent Poisson r.v.’s, where $A^c := V \setminus A$ is the complement of $A$. Moreover, $\lim_{t \to \infty} \inf_v \mathbb{E}_\lambda[Y_{v,A^c}(t)] = \lambda$. 

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Lemma 2.4. Let $G = (V, E)$ be an infinite $d$-regular graph. Let $w := (w_0, w_1, \ldots) \in V^{Z_+}$. For $t \in \mathbb{N} \cup \{\infty\}$ let $N_t(w)$ be the number of walkers not belonging to $W_{w_0}$ which for some $i \leq t$ visited $w_i$ at time $i$. Then $N_t(w)$ has a Poisson distribution for all $t$ and $w$ whose mean (under $P_\lambda$) is at least $c(d)\sqrt{t}$ for some constant $c(d)$ (depending only on $d$). In particular, $N_\infty(w)$ is infinite a.s.

The proofs of the last two lemmas involve straightforward applications of Fact 2.1 combined with the general bound $\sup_{x,y \in V} P^t(x, y) \leq \frac{C(d)}{\sqrt{t+1}}$ and are thus deferred to Appendix 9.

2.3 Insertion tolerance, translation invariance, ergodicity.

We now show how the SN model on a graph $G$ with a countable vertex set $V$ can be viewed as a long-range bond percolation process on $G$. This will allow us to use existing machinery from percolation theory in our study of the SN model.

Let $S := \{\{v, u\} : v \neq u, v, u \in V\}$. The standard form of a probability space of a long-range bond percolation process on $G$ is $((0,1)^S, P, \mathcal{F}_{\text{cylinder}})$, where $\mathcal{F}_{\text{cylinder}}$ is the cylinder $\sigma$-algebra, the minimal $\sigma$-algebra w.r.t. which $\{x \in \{0,1\}^S : x(s) = 1\}$ is measurable for all $s \in S$. Each $x \in \{0,1\}^S$ can be viewed as a graph $\text{graph}(x) = (V, E(x))$, where $s \in E(x)$ iff $x(s) = 1$, in which case we say $s$ is open in the configuration $x$. If $x(s) = 0$ we say that $s$ is closed in the configuration $x$. For $\mathcal{B} \in \mathcal{F}_{\text{cylinder}}$ we write $\text{graph}(\mathcal{B}) := \{\text{graph}(b) : b \in \mathcal{B}\}$.

Let $(\Omega, P, \mathcal{F})$ be a probability space in which there exist zero-one valued random variables $(Z_s)_{s \in S}$ ($S$ as above). This probability space gives rise to a (long-range bond) percolation process on $G$ as follows. For every $\omega \in \Omega$ we construct a graph $\text{graph}(\omega) = (V, E(\omega))$ by setting $s \in E(\omega)$ iff $Z_s(\omega) = 1$. Note that $\omega \rightarrow \text{graph}(\omega)$ need not be bijective.

Several definitions which we soon give take a simple form when the percolation process is given in the standard form. These definitions extend to the general case as follows. There is a canonical correspondence between $(\Omega, P, \mathcal{F})$ and a probability space having the standard form. For every $\omega \in \Omega$, we define $\psi(\omega) \in \{0,1\}^S$ by setting $\psi(\omega)(s) = Z_s(\omega)$. For every $\mathcal{B} \in \mathcal{F}$ set $\psi(\mathcal{B}) := \{\psi(b) : b \in \mathcal{B}\} \subseteq \{0,1\}^S$. Conversely, for every $x \in \{0,1\}^S$ we set $\psi^{-1}(x) := \{\omega \in \Omega : \psi(\omega) = x\}$ and for every $\mathcal{B} \subseteq \{0,1\}^S$ we set $\psi^{-1}(\mathcal{B}) := \bigcup_{x \in \mathcal{B}} \psi^{-1}(x)$. By abuse of notation, we identify the restriction of $P$ to the $\sigma$-algebra generated by $(Z_s)_{s \in S}$ with the space $(\{0,1\}^S, P_{\text{cylinder}}, \mathcal{F}_{\text{cylinder}})$, where for every $\mathcal{B} \in \mathcal{F}_{\text{cylinder}}$, $P_{\text{cylinder}}(\mathcal{B}) := P(\psi^{-1}(\mathcal{B}))$. That is, we identify $x \in \{0,1\}^S$ and $\mathcal{B} \in \mathcal{F}_{\text{cylinder}}$ with $\psi^{-1}(x)$ and $\psi^{-1}(\mathcal{B})$, respectively, and by abuse of notation write $P(\mathcal{B})$ for $P(\psi^{-1}(\mathcal{B}))$. In particular, we say that $P$ satisfies one of the properties defined below if $P_{\text{cylinder}}$ satisfies this property.

For every $x \in \{0,1\}^S$ and $s \in S$, we define $x^+_s \in \{0,1\}^S$ by setting

$$x^+_s(s') := \begin{cases} 1 & s' = s, \\
 x(s') & \text{otherwise.} \end{cases}$$
That is, $x^+_s$ is obtained from $x$ by flipping the value at $s$ to 1 if necessary, while keeping the the configuration unchanged elsewhere. For every $s \in S$ and $B \subseteq \{0, 1\}^S$ we define

$$B^+_s := \{ b^+_s : b \in B \}.$$  

Note that graph($B^+_s$) = $\{(V, E(b) \cup \{s\}) : b \in B\}$ (where as before graph($b$) = $(V, E(b))$; In other words, if we identify $B^+_s$ and $B$ with collections of graphs, then the former is obtained from the latter by adding to each graph in $B$ the edge $s$, if it did not already appear in it). We say that $P$ is insertion tolerant (also known as having positive finite energy) if for all $B \in \mathcal{F}_{\text{cylinder}}$ such that $P(B) > 0$ also $P(B^+_s) > 0$, for all $e \in E$.

Every $\varphi \in \text{Aut}(G)$ acts on $\{0, 1\}^S (\varphi : \{0, 1\}^S \rightarrow \{0, 1\}^S)$ via $\varphi(x)(s) = x(\varphi(s))$. Clearly, graph($\varphi(x)$) is isomorphic to graph($x$). We say that an event $A \in \mathcal{F}_{\text{cylinder}}$ is translation invariant if for all $\varphi \in \text{Aut}(G)$ we have that $A = \varphi(A)$, where $\varphi(A) := \{ \varphi(a) : a \in A \}$. We denote the $\sigma$-algebra of all translation invariant events by $\mathcal{I}$. We say that $P$ is translation invariant if for all $A \in \mathcal{F}_{\text{cylinder}}$ we have that $P(A) = P(\varphi(A))$ for all $\varphi \in \text{Aut}(G)$. When the percolation process is defined via Bernoulli random variables $(Z_s)_{s \in S}$, this is equivalent to the requirement that for all $\varphi \in \text{Aut}(G)$ we have that $(Z_s)_{s \in S} \overset{d}{=} (Z_{\varphi(s)})_{s \in S}$, where $\overset{d}{=}$ denotes equality in distribution. We say that $P$ is ergodic if $P(A) \in \{0, 1\}$ for all $A \in \mathcal{I}$.

**Proposition 2.5.** Let $G = (V, E)$ be an infinite connected vertex-transitive graph. Then for all $\lambda > 0$ we have that the law of $\text{AC}_t^\lambda(G)$ is translation invariant and ergodic for all $\lambda > 0$ and $t \in \mathbb{Z}_+ \cup \{\infty\}$.

When $G$ is a Cayley graph, it is straightforward to see that $\text{AC}_t^\lambda(G)$ is a factor of i.i.d.’s and hence is indeed translation invariant and ergodic. When $G$ is only assumed to be transitive one can still present $\text{AC}_t^\lambda(G)$ as a factor of i.i.d.’s, but this requires some care. We defer the proof of Proposition 2.5 to Appendix 11.

### 2.4 Couplings and stochastic domination

Let $G = (V, E)$ be a graph. As before, let $S := \{\{v, u\} : v \neq u, v, u \in V\}$. Equip $\{0, 1\}^S$ with the partial order $\leq$, where $x \leq y$ iff $x(s) \leq y(s)$ for all $s \in S$. We say that $A \in \mathcal{F}_{\text{cylinder}}$ is increasing if $x \in A$ and $x \leq y$ imply that also $y \in A$. For any two probability measures on $(\{0, 1\}^S, \mathcal{F}_{\text{cylinder}})$, $\mu$ and $\nu$, we say that $\mu$ stochastically dominates $\nu$ if $\mu(A) \geq \nu(A)$ for every increasing event $A \in \mathcal{F}_{\text{cylinder}}$.

Let $(X_s)_{s \in S}$ and $(Y_s)_{s \in S}$ be Bernoulli random variables defined on the same probability space $(\Omega, \mathcal{F}, \mathbb{P})$. Let the marginal distributions of $(X_s)_{s \in S}$ and $(Y_s)_{s \in S}$ under $\mathbb{P}$ be $\mu$ and $\nu$, respectively. Such a construction is called a coupling of $\mu$ and $\nu$. It is well-known and straightforward to show that if there exists such a coupling in which for all $s \in S$, $X_s \geq Y_s$ $\mathbb{P}$-a.s., then $\mu$ stochastically dominates $\nu$. Thus by Proposition 2.2:

**Proposition 2.6.** For every underlying graph $G$ for the SN model we have that for all $t \in \mathbb{Z}_+ \cup \{\infty\}$, the law of $\text{AC}_t^{\lambda_2}$ stochastically dominates the law of $\text{AC}_t^{\lambda_1}$ for all $\lambda_1 \leq \lambda_2$. 

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2.5 Non-amenability and the spectral radius

Let $G = (V, E)$ be a connected infinite regular graph. Let $\pi$ be the counting measure on $V$. The space of $L^2$ functions is given by $\ell^2(V, \pi) := \{f \in \mathbb{R}^V : \|f\|_2 < \infty\}$, where $\|f\|_2^2 := \langle f, f \rangle$ and $\langle f, g \rangle := \sum_v f(v)g(v)$. Let $K$ be a symmetric (i.e., $K(x, y) = K(y, x)$ for all $x, y \in V$) transition kernel of a Markov chain $(X_t)_{t=0}^{\infty}$ on $V$. We identify it with an operator by setting $(Kf)(x) := \sum_y P(x, y)f(y) = \mathbb{E}_x[f(X_1)]$. Its operator norm is given by

$$\|K\| := \sup\{\frac{\|Pf\|_2}{\|f\|_2} : f \in \ell^2(V, \pi), f \neq 0\} = \sup\{\frac{\langle Pf, f \rangle}{\|f\|_2^2} : f \in \ell^2(V, \pi), f \neq 0\} \quad (2.1)$$

(e.g., [11, Ex. 6.7]). Let $x, y \in V$ be arbitrary vertices. The spectral radius of $K$ is

$$\rho(K) := \limsup_{n \to \infty} [K^n(x, y)]^{1/n}. \quad (2.2)$$

It is standard that (see e.g., [11, p. 182-183]):

(1) The limit is independent of the choice of $x, y$.

(2) $\rho(K) = \|K\|$.

(3) $K^n(x, y) \leq [\rho(K)]^n$ for all $x, y$ and $n \geq 0$ (use $K^n(x, y) = \langle K^n1_x, 1_y \rangle$ and (2)).

Let $0 \leq p < 1$. Let $P_p$ be the transition kernel of LSRW on $G$ with holding probability $p$ (i.e., $P_p = pI + (1 - p)P_0$, where $P_0$ corresponds to simple random walk on $G$). Let $x, y \in V$ be arbitrary vertices. We denote the spectral radius of $P_p$ by

$$\rho_p := \limsup_{n \to \infty} (P^n_p(x, y))^{1/n}. \quad (2.3)$$

We denote the spectral radius of the SRW by $\rho(G) := \rho_0$. By (4) above

$$P^n_p(x, y) \leq \rho_p^n, \text{ for all } x, y \in V \text{ and } n \geq 0. \quad (2.4)$$

Thus having $\rho_p < 1$ is equivalent to having uniform exponential decay of the transition probabilities w.r.t. $P_p$. By (2) above, (2.1) and the fact that

$$\langle P_pf, f \rangle = p\langle f, f \rangle + (1 - p)\langle Pf, f \rangle$$

we have that

$$\rho_p = p + (1 - p)\rho(G), \quad (2.5)$$

and so $\rho(G) < 1$ iff $\rho_p < 1$ for all $p \in [0, 1)$.
3 Proof of Proposition 1.3

Proof. We first note that if \( \lambda_c > 0 \) and \( 0 < \lambda < \lambda_c \), then there exists a sequence \((u_n,v_n)_{n \in \mathbb{N}} \subseteq V \times V\) such that \( P(\lambda) [\text{FC}(u_n) = \text{FC}(v_n) \land u_n,v_n \in \Xi] \leq 2^{-n} \), for all \( n \). By (both parts of) the Borel-Cantelli Lemma, \( P(\lambda) \text{-a.s.} \) there exists some \( n \) such that \( \text{FC}(u_n) \neq \text{FC}(v_n) \) and \( u_n,v_n \in \Xi \). Indeed, on the one hand, a.s. there are only finitely many \( n \)'s such that \( \text{FC}(u_n) = \text{FC}(v_n) \) and \( u_n,v_n \in \Xi \), while on the other hand, a.s. there are infinitely many \( n \)'s such that \( u_n,v_n \in \Xi \). Thus a.s. there exists some \( n \) such that \( u_n,v_n \in \Xi \) and \( \text{FC}(u_n) = \text{FC}(v_n) \). Thus \( P(\lambda)[\text{Con}] = 0 \), as desired.

Conversely, fix some \( \lambda > \lambda_c \geq 0 \). We shall show that \( P(\lambda)[\text{Con}] = 1 \). By definition of \( \lambda_c \) (and the monotonicity of the model w.r.t. \( \lambda \))\(^1\) there exists some \( p > 0 \) such that \( \inf_{u,v} P(\lambda)[\text{FC}(u) = \text{FC}(v) \mid u,v \in \Xi] \geq p \) for all \( \lambda' \geq \frac{\lambda_c + \lambda}{2} \). Fix some \( u,v \in V \). Let us condition on \( u,v \in \Xi \). Let \( B_r \) be the ball of radius \( r \) around \( u \). Let \( D_t \) be the event that there exist some \( k \in \mathbb{N} \) and some \( u_1 = u, u_2, \ldots, u_{k+1} = v \) all belonging to \( D_t \) such that \( u_i \not\sim u_{i+1} \) for all \( 1 \leq i \leq k \). Since \( D_t \uparrow \{ u \sim v \} \) as \( t \to \infty \) (recall that a path of acquaintances has a finite length) there exists a finite time \( t_1 \) and some finite set \( A_1 \subseteq V \) (both may depend on \( u,v \)), such that w.p. at least \( p/2 \), there exists a path of acquaintances between the walkers from \( W_u \) and \( W_v \) by time \( t_1 \), which only uses walkers from \( W_{A_1} := \bigcup_{a \in A_1} W_a \). We think of this as the “first trial” to connect the walkers in \( W_u \) to those in \( W_v \).

Using the regeneration Lemma we show that after each failed trial, there will be another trial whose success probability is at least \( p/2 \), regardless of the information exposed in all previous trials. All trials involve some finite set of walkers and a finite amount of time (both may depend on the information exposed in previous trials).

Denote by \( Y_{a,1}(t) \) the number of walkers not from \( W_{A_1} \) which are at vertex \( a \) at time \( t \). By Lemma 2.3, there exists some \( s_1 \) so that \( (Y_{a,1}(s))_{a \in V} \) stochastically dominate i.i.d. \( \text{Pois}(\lambda_2) \) random variables for all \( s \geq s_1 \), where \( \lambda_2 := \lambda_c + \frac{3(\lambda_0 - \lambda_c)}{4} \). We may assume that \( s_1 = t_1 \) by increasing one of them if necessary. Pick some \( w_u \in W_u \) and \( w_v \in W_v \) and let \( (w_u(t))_{t=0}^\infty, (w_v(t))_{t=0}^\infty \) be the LSRWs they perform, respectively. Let \( W_a(t) \) be the collection of walkers which are at vertex \( a \) at time \( t \).

Repeating the same reasoning as before (with \( \lambda_2 = \lambda_c + \frac{3(\lambda_0 - \lambda_c)}{4} \) in the role of \( \lambda \)) yields that there must exist some \( t_2 > t_1 \) and some finite set \( A_2 \subseteq V \) (both may depend on \( (w_v(t_1), w_u(t_1)) \)) such that given the walks performed by the walkers in \( A_1 := W_{A_1} \) by time \( t_1 \) (and that the first trial failed) we have that (i)-(ii) below hold:

\(^1\)Actually, we are using here also the fact that the Poisson(\( \lambda \)) distribution conditioned on being positive is stochastically increasing in \( \lambda \). To see this, consider the number of points in \([0,1]\) for a rate \( \lambda \) Poisson process. Observe that conditioned on having at least 1 point, the location of the first point is stochastically decreasing in \( \lambda \). Given that the first point is at \( x \) the number of additional points has a Pois(\( \lambda(1-x) \)) distribution (which is stochastically decreasing in \( x \) and increasing in \( \lambda \)). We leave the remaining details to the reader.
(i) The conditional probability that \( w_u \) and \( w_v \) have a path of acquaintances by time \( t_2 \) which uses only walkers from \((A_2 \setminus A_1) \cup \{w_v, w_u\}\) where \( A_2 := \cup_{a \in A_2} W_a(t_1) \), and all the acquaintances along this path were made between time \( t_1 \) and \( t_2 \) (ignoring possible earlier acquaintances if such occurred), is at least \( p/2 \).

(ii) \((Y_{a,2}(t_2))_{a \in V}\) stochastically dominate i.i.d. \( \text{Pois} (\lambda_3) \) r.v.’s, where \( \lambda_3 := \lambda_c + \frac{5(\lambda - \lambda_c)}{8} \) and \( Y_{a,2}(t_2) \) is the number of walkers, not from \( A_1 \cup A_2 \), which are at \( a \) at time \( t_2 \).

It is clear how to continue. Namely, by induction on \( i \) one can argue that there exist \( t_{i+1} \) and finite sets \( A_1, \ldots, A_{i+1} \subset V \) and \( A_j := \cup_{a \in A_j} W_a(t_{j-1}) \) for \( j \in [i+1] \) (where \( t_0 := 0 \) and both \( t_{i+1} \) and \( A_{i+1} \) may depend on \((w_v(t_{i+1}), w_u(t_{i+1}))\)) such that \( t_{i+1} > t_i \) and given the walks performed by the walkers in \( \cup_{j \in [i]} A_j \) by time \( t_i \) we have that (i)-(ii) below hold:

(i) The conditional probability that \( w_u \) and \( w_v \) have a path of acquaintances by time \( t_{i+1} \) which uses only walkers in
\[
(A_{i+1} \setminus \cup_{j=1}^i A_j) \cup \{w_v, w_u\},
\]
and all the acquaintances along this path were made between time \( t_i \) and \( t_{i+1} \) (ignoring possible earlier acquaintances if such occurred) is at least \( p/2 \).

(ii) \((Y_{a,i+1}(t_{i+1}))_{a \in V}\) stochastically dominate i.i.d. \( \text{Pois} (\lambda_{i+2}) \) random variables, where \( \lambda_{i+2} := \lambda_c + \frac{(2i+1+1)(\lambda - \lambda_c)}{2^{i+2}} \) and \( Y_{a,i+1}(t_{i+1}) \) is the number of walkers, not from \( \cup_{j \in [i+1]} A_j \), which are at \( a \) at time \( t_{i+1} \).

As each trial has success probability at least \( p/2 \), regardless of the result of the previous rounds, a.s. one of the trials will be successful, where here success means that the event from (i) occurs.

\[\square\]

4 The amenable case

We shall utilize the following theorem, taken from [6], in our analysis of the amenable case. We note that in [6] only the graphs \( \mathbb{Z}^d \) for \( d \in \mathbb{N} \) (or some half spaces) were considered. However their analysis can easily be extended to all amenable vertex-transitive graphs.

**Theorem 4.1.** Let \( G = (V, E) \) be an infinite connected vertex-transitive graph. Let \((\Omega, P)\) be a translation invariant long range bond percolation process on \( G \) possessing insertion tolerance. Then \( P[\text{there exists at most one infinite connected component}] = 1 \).

Note that for all \( \mathcal{B} \in \mathcal{F}_{\text{cylinder}} \) and \( e = \{u, v\} \in E \), by planting additional walkers at \( u \) and \( v \) (this is done in the proof below) we see that for \( \mathcal{A} := \text{graph}(\mathcal{B}) \) we have that
\[
P_\lambda[\text{AC} \in \mathcal{A}] > 0 \implies P_\lambda[\text{AC} \in \hat{\mathcal{A}}_e] > 0,
\]
where $\hat{A}_e := \{(V, F) : e \in F, F \supseteq F'\}$ for some $(V, F') \in \mathcal{A}$ is the collection of all graphs obtained by adding to each graph in $\mathcal{A}$ some collection of edges containing $e$.

The problem is that planting additional walkers at $u$ and $v$ might add more than just the edge $\{u, v\}$ to AC (thus this idea cannot be used to establish insertion tolerance). In order to utilize Theorem 4.1, we construct an auxiliary model, stochastically dominated by the SN model, to which this idea applies. In order to ensure we can add to the obtained graph with positive probability an edge $e$ and only that edge, in the auxiliary model the planted walkers can only make acquaintances at time 1.

**Theorem 4.2.** Let $G = (V, E)$ be an infinite connected vertex-transitive amenable graph. Then $\lambda_c = 0$.

*Proof.* Let $\lambda > 0$. We partition the particles into two independent sets, $\mathcal{W}^1$, $\mathcal{W}^2$ of density $\lambda/2$ each. We may consider the evolution of the model only w.r.t. $\mathcal{W}^1$ (as if $\mathcal{W}^2$ does not exist). Denote the obtained acquaintances graph w.r.t. $\mathcal{W}^1$ for time $\infty$ by $H := (V, E_1)$. Denote the degree of $G$ by $d$. We now partition $\mathcal{W}^2$ into $d$ sets of density $\lambda/(2d)$ as follows. For $v \in V$ let $N(v) := \{u \in V : \{u, v\} \in E\}$ be the set of its neighbors. Let $\mathcal{W}^i_v$ be the particles in $\mathcal{W}^i$ (where $i \in \{1, 2\}$) which initially occupy $v$. We partition it into $d$ sets: $\mathcal{W}(v, u)$ for $u \in N(v)$. Let $E_2 \subseteq E$ be the collection of edges $\{u, v\} \in E$ such that there is some particle $w \in \mathcal{W}(v, u)$ and some particle $w' \in \mathcal{W}(u, v)$ which met at time 1 (note that this is always possible as we take the holding probability to be positive).

Let $H_1 := (V, E_1 \cup E_2)$. Note that by Poisson thinning the events $\{e \in E_2\}$ are independent for different $e \in E$ and thus $H_1$ is insertion tolerant. The proof of translation invariance of the SN model, with minor adaptations can easily be extended to show that the law of $H_1$ is translation invariant.

We may switch the roles of $\mathcal{W}^1$ and $\mathcal{W}^2$ in the above construction and now partition each $\mathcal{W}^i_v$ further into $d$ sets $\mathcal{W}(v, u)$ for $u \in N(v)$ to get: $\hat{H} := (V, \hat{E}_1)$ the acquaintances graph for time $\infty$ defined only w.r.t. $\mathcal{W}^2$ and $\hat{E}_2 \subseteq E$ the collection of $\{u, v\} \in E$ such that there is some particle $w \in \hat{W}(v, u)$ and some particle $w' \in \hat{W}(u, v)$ which met at time 1. By symmetry also $H_2 := (V, \hat{E}_1 \cup \hat{E}_2)$ is insertion tolerant and translation invariant.

Clearly, $\hat{H} := (V, E_1 \cup E_2 \cup \hat{E}_1 \cup \hat{E}_2)$ is a subgraph of the (usual) acquaintances graph for time $\infty$ (when the walkers are not partitioned into different sets). Thus it suffices to argue that a.s. it has a unique infinite connected component containing all $u \in \Xi = \{v : \mathcal{W}_v \neq \emptyset\}$.

It follows from Theorem 4.1 that both $H_1$ and $H_2$ a.s. have at most one infinite connected component. Now if $\mathcal{W}_v \neq \emptyset$, then $\mathcal{W}_i^v \neq \emptyset$ for some $i \in \{1, 2\}$. It is not hard to verify that for all positive $\lambda'$, the SN model with particle density $\lambda'$ satisfies that every $u \in \Xi$ lies in an infinite connected component of the acquaintances graph for time $\infty$, as every walker meets infinitely many other walkers by time $\infty$ (this follows from Lemma 2.4). By uniqueness it follows that every $v$ such that $\mathcal{W}_v \neq \emptyset$ lies in the same infinite connected component of $H_i$. As a.s. there is some $v$ such that both $\mathcal{W}_1^v \neq \emptyset$ and $\mathcal{W}_2^v \neq \emptyset$ it follows that $\hat{H}$ has a unique infinite connected component containing all $u \in \Xi$. \qed
5 An upper bound on the critical density in the non-amenable setup.

Theorem 5.1. Let \( G = (V, E) \) be a \( d \)-regular connected infinite non-amenable graph. Denote the spectral radius of LSRW with holding probability \( 1/(d + 1) \) (respectively, \( 1/2 \)) by \( \rho \) (respectively, \( \rho_{1/2} \)). If the holding probability of the walks is \( 1/(d + 1) \) (respectively, \( 1/2 \)) then \( \lambda_c \leq (d + 1 + \frac{2}{1 - \rho}) \log 8 \) (respectively, \( \lambda_c \leq 20 \log d/(1 - \rho_{1/2}) \)).

We first explain the main idea behind the proof of Theorem 5.1 in simple words, in a slightly simpler setup. We concentrate here on the case that the holding probability is given \( \lambda \) in each walker which crossed from \( u = u_0 \) to \( \hat{u}_1 \) has a \( \operatorname{Pois}(\lambda/(d + 1)) \) distribution.

Fix some \( \lambda \leq \lambda/(d + 1) \) to be determined shortly. By Poisson thinning we can look at time one at a subset \( \mathcal{W}(1) \) of them whose size has a \( \operatorname{Pois}(\alpha) \) distribution (namely, by including in it each walker which crossed from \( u_0 \) to \( \hat{u}_1 \) at time 1 w.p. \( \alpha/\lambda/(d + 1) \)) independently. If it is not empty, we set \( u_1 := \hat{u}_1 \), otherwise, we set \( u_1 \) to be the location of \( w \) at time 1.

Assume by induction that we have defined the vertices \( u_0, u_1, \ldots, u_i \) and \( \hat{u}_1, \ldots, \hat{u}_i \) as well as disjoint sets of walkers \( \mathcal{W}(1), \ldots, \mathcal{W}(i) \), such that for all \( j \in [i] \) the size of \( \mathcal{W}(j) \) has a \( \operatorname{Pois}(\alpha) \) distribution (given the information exposed up to the time \( \mathcal{W}(j) \) was defined; i.e., given \( \mathcal{W}(1), \ldots, \mathcal{W}(j - 1) \) as well as \( u_0, u_1, \ldots, u_{j-1} \) and \( \hat{u}_1, \ldots, \hat{u}_{j-1} \)), and this is a subset of the set of walkers which was at \( u_{j-1} \) at time \( j - 1 \) and then moved to \( \hat{u}_j \) at time \( j \), where \( \hat{u}_j \) is some neighbor of \( u_{j-1} \) which is closer to \( v \) than \( u_{j-1} \) is. If \( |\mathcal{W}(j)| > 0 \) we set \( u_j := \hat{u}_j \). Otherwise, we set \( u_j \) to be a vertex closest to \( v \) which is occupied at time \( j \) by some walker from \( \cup_{m=0}^{j-1} \mathcal{W}(m) \) (where \( \mathcal{W}(0) := \{w\} \)).

Observe that if \( \alpha \) is sufficiently large, then the sequence \( \{u_i : i \in \mathbb{Z}_+\} \) has a positive drift towards \( v \). In order for this construction to work, it is necessary that the distribution of the number of walkers which are at \( u_i \) at time \( i \), which do not belong to \( \cup_{m=0}^{j-1} \mathcal{W}(m) \), will stochastically dominate the \( \operatorname{Pois}(\alpha(d + 1)) \) distribution. In fact, it is not hard to prove by induction that for all \( a_1, \ldots, a_i, \hat{a}_1, \ldots, \hat{a}_{i-1} \in V \) conditioned on \( u_0 = a_0, u_1 = a_1, \ldots, u_i = a_i \) and \( \hat{u}_1 = \hat{a}_1, \ldots, \hat{u}_{i-1} = \hat{a}_{i-1} \) the aforementioned law is a Poisson with parameter \( \lambda - \alpha \sum_{j=1}^i p_j \), where \( p_j = P^{i-j}(a_j, a_i) \) is the probability of a given walker from \( \mathcal{W}(j) \) to be at \( u_i \) at time \( i \). Clearly, \( p_j \leq \sup_{x,y} P^{i-j}(x, y) \leq \rho^{i-j} \). We get that \( \lambda - \alpha \sum_{j=1}^i p_j \leq \lambda - \alpha/(1 - \rho) \), and thus the construction is indeed possible, provided
that \( \lambda \) is sufficiently large. Crucially, after conditioning on \( u_0 = a_0, u_1 = a_1, \ldots, u_i = a_i \) and \( \hat{u}_1 = \hat{a}_1, \ldots, \hat{u}_{i-1} = \hat{a}_{i-1} \) as above, using the induction hypothesis the induction step requires only a standard use of Poisson thinning.

**Proof of Theorem 5.1.** First consider the case that the holding probability is \((d + 1)^{-1}\). Fix some \( u, v \in \Xi \) and \( \lambda > (d + 1 + \frac{2}{1 - p'}) \log 8 \). We shall construct two random paths (more precisely, two sequences of vertices) \( \gamma, \gamma' \) such that the walkers which are at \( \gamma_t \) (respectively, \( \gamma'_t \)) at time \( \ell + t \) (for some \( \ell \) to be determined below) are in \( FC(v) \) (respectively, \( FC(u) \)).

Denote the natural filtration of \((\gamma_t, \gamma'_t)_{t \geq 0}\) by \( \mathcal{F}_t \). We will show that there exists some \( c > 0 \) such that for all \( t \) on the event \( d(\gamma_t, \gamma'_t) > 0 \) we have \( E_\lambda[d(\gamma_{t+1}, \gamma'_{t+1}) - d(\gamma_t, \gamma'_t) | \mathcal{F}_t] \leq -c \), (where \( d(\cdot, \cdot) \) is the graph distance, i.e., the paths have a bias towards each other). This clearly implies that given that \( u, v \in \Xi \), we have that \( FC(u) = FC(v) \) \( P_\lambda \)-a.s..

Fix some \( \alpha > \log 8 \) such that \( \lambda > (d + 1 + \frac{2}{1 - p'}) \alpha \). At time 0 expose some \( w_v \in \mathcal{W}_v =: \mathcal{A}_0, w_u \in \mathcal{W}_u =: \mathcal{B}_0 \) and their locations at time \( \ell \) and set \( \gamma_0 \) and \( \gamma'_0 \) to be these locations, resp., where \( \ell \) is sufficiently large so that the distribution of the number of walkers, not belonging to \( \mathcal{A}_0 \cup \mathcal{B}_0 \) at the different vertices of \( G \) at all times \( t \geq \ell \), stochastically dominates that of i.i.d. \( \text{Pois}(\lambda') \) random variables, where \( \lambda' := \alpha(d + 1 + \frac{2}{1 - p'}) \). In other words,

\[
\inf_{\ell, a \in V} \kappa_\ell(a) \geq \lambda', \text{ where } \kappa_\ell(a) := \lambda(1 - P^\ell(u,a) - P^\ell(v,a)). \tag{5.1}
\]

Recall that for \( v \in V \) and \( t \in \mathbb{Z}_+ \) we define \( \mathcal{W}_e(t) \) as the set of walkers occupying \( v \) at time \( t \). For an oriented edge (possibly a loop) \( e = (e^-, e^+) \) let

\[
\mathcal{W}_e(t) := \mathcal{W}_{e^-}(t) \cap \mathcal{W}_{e^+}(t + 1)
\]

be the collection of all walkers whose positions at times \( t \) and \( t + 1 \) are \( e^- \) and \( e^+ \), respectively. Clearly, it suffices to describe the construction of \( \gamma, \gamma' \) only until the first \( k \) for which \( \gamma_k = \gamma'_k \). We define \( \gamma, \gamma' \) inductively as follows. Assume that \( (\gamma_i, \gamma'_i)_{i=0}^{k-1} \) and some collection of oriented edges \( e_1, f_1, \ldots, e_{k-1}, f_{k-1} \), have already been defined and that for all \( 1 \leq i < k \) in the \( i \)-th step of the construction we first define \( e_i \), then (as described in (3) below) expose a certain set of walkers \( \mathcal{A}_i \subseteq \mathcal{W}_{e_i}(\ell + i - 1) \) and define \( \gamma_i \) (as described below in (2)), after which we define \( f_i \), expose a set of walkers \( \mathcal{B}_i \subseteq \mathcal{W}_{f_i}(\ell + i - 1) \) and finally define \( \gamma'_i \), such that the following hold (the construction is described only in (2) and (3), while (4)-(5) are included as part of the induction hypothesis only for the purpose of facilitating the induction step):

1. \( \gamma_i \neq \gamma'_i \) for all \( i < k \) (otherwise, the construction is concluded before stage \( k \)).

2. For all \( 1 \leq i < k \), the edge \( e_i = (e^-_i, e^+_i) \) is some oriented edge in \( G \) of the form \( e_i = (\gamma_{i-1}, \nu_i) \) satisfying that \( \nu_i, \gamma'_{i-1} = d(\nu_i, \gamma'_{i-1}) = d(\gamma_{i-1}, \gamma'_{i-1}) - 1 \) (i.e., \( \nu_i \) is some neighbor of \( \gamma_{i-1} \) which is closer to \( \gamma'_{i-1} \) than \( \gamma_{i-1} \) is). The sets \( \mathcal{A}_0, \mathcal{B}_0, \ldots, \mathcal{A}_{i-1}, \mathcal{B}_{i-1} \) have already been defined, as described in (3) below. The set \( \mathcal{A}_i \) is then defined inductively in a manner
described in (3) below so that given $|A_0|, |B_0|, \ldots, |A_{i-1}|, |B_{i-1}|, e_1, f_1, \ldots, e_{i-1}, f_{i-1}$ and $(\gamma_j, \gamma_j')_{j=0}^{i-1}$

$$A_i \subseteq \mathcal{R}_i := \mathcal{W}_{e_i}(\ell + i - 1) \setminus \bigcup_{j=0}^{i-1} (A_j \cup B_j) \quad \text{and} \quad |A_i| \sim \text{Pois}(\alpha). \quad (5.2)$$

If $|A_i| \geq 1$, we set $\gamma_i = v_i = e_i^+$. Otherwise, we define $\gamma_i$ to be some vertex occupied at time $\ell + i$ by some walker in $\bigcup_{j=0}^{i-1} A_j$ of minimal distance from $\gamma_{i-1}'$.

Similarly, after defining $\gamma_i$, we set $f_i = (f_i^-, f_i^+)$ to be of the form $f_i = (\gamma_i', u_i)$ satisfying that $d(\gamma_i, u_i) = d(\gamma_i, \gamma_i') - 1$ if $\gamma_i \neq \gamma_i'$; otherwise, we set $u_i := \gamma_i$. As before, we then define the set $\mathcal{B}_i$ inductively in a manner described in (3) below so that given $|A_0|, |B_0|, \ldots, |A_{i-1}|, |B_{i-1}|, |A_i|, e_1, f_1, \ldots, e_{i-1}, f_{i-1}, e_i, \gamma_i$ and $(\gamma_j, \gamma_j')_{j=0}^{i-1}$

$$\mathcal{B}_i \subseteq \mathcal{R}_i' := \mathcal{W}_{f_i}(\ell + i - 1) \setminus \bigcup_{j=0}^{i-1} (A_j \cup B_j) \quad \text{and} \quad |\mathcal{B}_i| \sim \text{Pois}(\alpha). \quad (5.3)$$

If $|\mathcal{B}_i| \geq 1$, we set $\gamma_i' = u_i = f_i^+$. Otherwise, we define $\gamma_i'$ to be some vertex occupied at time $\ell + i$ by some walker in $\bigcup_{j=0}^{i-1} B_j$ of minimal distance from $\gamma_i$.

(3) The sets $A_1, B_1, \ldots, A_{k-1}, B_{k-1}$ are all disjoint and their sizes are i.i.d. Pois($\alpha$). Denote

$$\beta_i(y) := \sum_{j=1}^{i-1} (E[|A_j|]P^{i-j-1}(e_j^+, y) + E[|B_j|]P^{i-j-1}(f_j^+, y))$$

$$= \alpha \sum_{j=0}^{i-2} (P^j(e_{i-j-1}^+, y) + P^j(f_{i-j-1}^+, y)) \leq 2\alpha \sum_{j \geq 0} \rho^j = 2\alpha/(1 - \rho). \quad (5.4)$$

Let $\mathcal{R}_i$ and $\mathcal{R}_i'$ be as in (5.2)-(5.3). Let $\kappa_i(\cdot)$ and $\beta_i(\cdot)$ be as in (5.1) and (5.4). Then, for all $i < k$ given $e_1, f_1, \ldots, e_{i-1}, f_{i-1}$, we have that $|\mathcal{R}_{i-1}|$ and $|\mathcal{R}'_{i-1}|$ are independent Poisson r.v.'s,

$$E[|\mathcal{R}_i| \mid e_1, f_1, \ldots, e_{i-1}, f_{i-1}, e_i] = P(e_i^+, \kappa_{i+\ell-1}(e_i^+) - \beta_i(e_i^+)) \geq \frac{1}{\sigma+1} (\lambda - 2\alpha/(1 - \rho)) \geq \alpha,$$

$$E[|\mathcal{R}_i'| \mid e_1, f_1, \ldots, e_i, f_i] = P(f_i^+, \kappa_{i+\ell-1}(f_i^+) - \beta_i(f_i^+)) \geq \alpha. \quad (5.5)$$

For all $i < k$, the set $A_i$ (respectively, $B_i$) is a random subset of $\mathcal{R}_i$ (respectively, $\mathcal{R}_i'$) obtained from it by including in $A_i$ (respectively, $B_i$) every element of $\mathcal{R}_i$ (respectively, $\mathcal{R}_i'$) independently w.p. $p_i := \alpha/E[|\mathcal{R}_i| \mid e_1, f_1, \ldots, e_{i-1}, f_{i-1}, e_i]$ (respectively, $p_i' := \alpha/E[|\mathcal{R}_i'| \mid e_1, f_1, \ldots, e_i, f_i]$). Note that by (5.5) $p_i, p_i' \leq 1$.

(4) For $i < k$ and every walk $w := (w_0, \ldots, w_{\ell+1})$ with $w_0 \notin \{u, v\}$, given $e_1, f_1, \ldots, e_{i-1}, f_{i-1}$, the number $Q_w$ of walkers not belonging to $\bigcup_{j=0}^{i-1} (A_j \cup B_j)$ which performed the walk $w$
has a Poisson distribution.\[^2\]
Moreover, for each fixed \(i < k\), given \(e_1, f_1, \ldots, e_{i-1}, f_{i-1}\), the \(Q_w\)'s (where \(w\) is as above, of length \(\ell + i\)).

(5) Consequently, for all \(i \leq k\) the number \(U^i_y\) of walkers not belonging to \(\bigcup_{j=0}^{j-1} (A_j \cup B_j)\) which are at vertex \(y\) at time \(\ell + i - 1\), has a Poisson distribution (by (4)) with mean \(\kappa_{i+\ell-1}(y) - \beta_i(y)\). Finally, for each fixed \(i \leq k\) we have that \((U^i_y)_{y \in V}\) are mutually independent.

In order to define \(e_k, A_k, \gamma_k, f_k, B_k, \gamma_k'\) (in this order) we apply steps (2) and (3) with \(k\) in the role of \(i\). It is not hard to see that by the induction hypotheses (3)-(5) together with Poisson thinning and (5.5) (with \(i = k\)), this extends the construction by one step so that (2)-(5) remain valid for \(k+1\) in the role of \(k\). We leave the details to the reader.

Note that \(d(\gamma_k, \gamma_{k-1}') - d(\gamma_{k-1}, \gamma_{k-1}' - 1) \leq 1\) and that also \(d(\gamma_k, \gamma_k') - d(\gamma_k, \gamma_{k-1}') \leq 1\). By step (2) the first increment equals \(-1\) w.p. at least \(\mathbb{P}(\text{Pois}(\alpha) > 0) = 1 - e^{-\alpha} > 7/8\) and the same holds for the second increment, unless \(\gamma_k = \gamma_k'\), in which case the second increment equals \(0\) w.p. at least \(1 - e^{-\alpha} > 7/8\). Thus \(\gamma\) and \(\gamma'\) are indeed biased towards each other as desired.

We now consider the case of holding probability \(1/2\). We explain the necessary adaptations leaving some of the details to the reader. Set \(\lambda = \frac{20 \log d}{1 - p_{1/2}}\). As before let \(\gamma_0\) and \(\gamma_0'\) be the positions of \(w_v\) and \(w_u\) at time \(\ell\), respectively, where \(\ell\) is so that the distribution of the number of walkers, other than \(w_u\) and \(w_v\), at the different vertices of \(G\) at time \(\ell\) stochastically dominates that of i.i.d. \(\text{Pois}(\lambda')\) for some \(\lambda' > \frac{20 \log d}{1 - p_{1/2}} - 1\).

Assume that for some collection of oriented edges \(e_1, f_1, \ldots, e_{k-1}, f_{k-1}\) the sequence \((\gamma_i, \gamma_i')_{i=0}^{k-1}\) has been defined and that in the \(i\)-th step of the construction we exposed sets of walkers

\[
\begin{align*}
A_i &\subseteq W_{e_i}(\ell + i - 1), \\
C_i &\subseteq W_{\gamma_{i-1}, \gamma_{i-1}'}(\ell + i - 1) = W_{\gamma_{i-1}}(\ell + i - 1) \cap W_{\gamma_{i-1}'}(\ell + i), \\
B_i &\subseteq W_{f_i}(\ell + i - 1) \quad \text{and} \\
D_i &\subseteq W_{\gamma_{i-1}', \gamma_{i-1}'}(\ell + i - 1) = W_{\gamma_{i-1}'}(\ell + i - 1) \cap W_{\gamma_{i-1}'}(\ell + i),
\end{align*}
\]

so that

(i) \(A_1, B_1, C_1, D_1, \ldots, A_{k-1}, B_{k-1}, C_{k-1}, D_{k-1}\) are all disjoint;

\[^2\] The exact expression for the mean shall not be used in what comes. It is given by \(\lambda p(w) \prod_{j \in I_w}(1 - p_j) \prod_{j' \in J_w}(1 - p'_j)\), where \(p_j\) and \(p'_j\) are as in (3) and \(p(w)\) is as in §2.1, and where

\[
\begin{align*}
I_w &:= \{1 \leq j < i : (w_{\ell+j-1}, w_{\ell+j}) = e_j\} \quad \text{and} \\
J_w &:= \{1 \leq j < i : (w_{\ell+j-1}, w_{\ell+j}) = f_j\}.
\end{align*}
\]
(ii) $|A_1|, |B_1|, \ldots, |A_{k-1}|, |B_{k-1}|$ are i.i.d. Pois$(2d^{-1} \log d)$;

(iii) $|C_1|, |D_1|, \ldots, |C_{k-1}|, |D_{k-1}|$ are i.i.d. Pois$(4 \log d)$ and

(iv) $|A_1|, |B_1|, |C_1|, |D_1|, \ldots, |A_{k-1}|, |B_{k-1}|, |C_{k-1}|, |D_{k-1}|$ are independent.

We set $e_k = (\gamma_{k-1}, v_k)$ to be some oriented edge in $G$ so that $d(v_k, \gamma'_{k-1}) = d(\gamma_{k-1}, \gamma'_{k-1}) - 1$ and expose a subset $A_k$ of $W_{e_k}(\ell + k)$ and a subset $C_k$ of $W_{\gamma_{k-1}}(\ell + k - 1) \cap W_{\gamma_{k-1}}(\ell + k)$, disjoint of the previously exposed sets of walkers, so that $|A_k| \sim$ Pois$(2d^{-1} \log d)$ and $|C_k| \sim$ Pois$(4 \log d)$. A similar calculation as in the case of holding probability $1/(d + 1)$ shows that one can construct such $(A_k, C_k)$. We defer the calculation to the end of the proof, as to not disrupt the flow of the argument.

If $|A_k| > 0$ we set $\gamma_k = v_k$. If $|A_k| = 0$ but $|C_k| > 0$ we set $\gamma_k = \gamma_{k-1}$. If $|A_k| = 0 = |C_k|$, we define $\gamma_k$ to be some vertex occupied at time $\ell + k$ by some walker in $\bigcup_{i=0}^{k-1} (A_i \cup C_i)$ of minimal distance from $\gamma'_{k-1}$.

We define $B_k, D_k$ and $\gamma'_k$ in an analogous manner (with $\gamma_k$ here taking the role of $\gamma'_{k-1}$ in the construction of $A_k, C_k$ and $\gamma_k$). Finally, note that each of the increments $d(\gamma_k, \gamma'_{k-1}) - d(\gamma_{k-1}, \gamma'_{k-1})$ and $d(\gamma_k, \gamma'_k) - d(\gamma_{k-1}, \gamma'_k)$ is in $\{0, \pm 1\}$ and has mean at most

$$-1 \times \Lambda(|A_k| \geq 1) + 1 \times \Lambda(|A_k| = 0) \Lambda(|C_k| = 0)$$

$$= -P[\text{Pois}(2d^{-1} \log d) \geq 1] + P[\text{Pois}(2d^{-1} \log d) = 0]P[\text{Pois}(4 \log d) = 0]$$

$$= -(1 - e^{-2d^{-1} \log d}) + e^{-2d^{-1} \log d} e^{-4 \log d} < -d^{-1} \log d + d^{-4} < 0.$$

To conclude the proof we now provide a sketch proof for the existence of $(A_k, C_k)$ and $(B_k, D_k)$ as above. The key calculation is that by induction, given $e_1, f_1, \ldots, e_{k-1}, f_{k-1}$, for all $i < k$ the loss to the expected number of particles at $\gamma_{k-1}$ at time $k - 1 + \ell$ due to the fact we are not counting particles from $A_i, B_i, C_i, D_i$ is respectively, $2d^{-1} \log d \times P^{k-i}(e_i^+, \gamma_{k-1})$,

$4 \log d \times P^{k-i}(e_i^-, \gamma_{k-1})$,

$2d^{-1} \log d \times P^{k-i}(f_i^+, \gamma_{k-1})$ and

$4 \log d \times P^{k-i}(f_i^-, \gamma_{k-1})$. Summing over these four sets and over $i < k$ the total contribution is at most

$$(8 \log d + 4d^{-1} \log d)/(1 - \rho_{1/2}).$$

Thus given $e_1, f_1, \ldots, e_{k-1}, f_{k-1}$, the the number of walkers at $\gamma_{k-1}$ at time $k - 1 + \ell$ which do not belong to either of the sets $A_1, B_1, C_1, D_1, \ldots, A_{k-1}, B_{k-1}, C_{k-1}, D_{k-1}$ has a Poisson distribution with mean at least $\lambda' - (8 \log d + 4d^{-1} \log d)/(1 - \rho_{1/2}) \geq 8 \log d$. The existence of $(A_k, C_k)$ now follows from Poisson thinning. The proof of the existence of $(B_k, D_k)$ is analogous.

6 The $d$-regular tree - Proof of Theorem 2.

Let us first explain the main idea behind the proof of Theorem 2. As explained below, the lower bound on $\lambda_c$ follows from Theorem 8.1. So our goal is to sketch the proof that for
some $C, p > 0$, when $\lambda \geq C \sqrt{d}$ we have that for all $u, v \in V$ we have that $u \sim v$ w.p. at least $p$. We now sketch a construction from which we deduce that with positive probability there are infinitely many times $t$ at which $u$ is visited by some walker $w$ which is at time $t$ in the friend cluster of some walker in $W_u$, and $t$ is the first time that $w$ visits $u$.

With slightly more care, in the proof below we manage to perform a small modification of the construction, and deduce that in fact w.p. at least $p$ there are infinitely many times $t$ as above at which we have that in addition $v$ is visited by some walker $w'$ which is at time $t$ in the friend cluster of some walker in $W_v$, and $t$ is the first time that $w'$ visits $v$. Clearly, on this event a.s. $u \sim v$ (as at each such time $t$ we get two new walkers at $u$ and $v$, and these pair of walkers have some probability of meeting each other).

For simplicity assume that $d := 2\ell + 1$ is odd and that $\ell \geq 2$. Set $u$ as the root of $T_d$. We say that a child of $u$ is a left child if it is one of the $\ell + 1$ leftmost children of $u$ and otherwise it is a right child. Similarly, for $z \neq u$ we say that a child of $z$ is a left child if it is one of the $\ell$ leftmost children of $z$ and otherwise it is a right child. Let $\mathcal{T}$ be the induced tree on $u$ and the vertices which are right children and the path between them and $u$ contains only right children (apart from $u$).

Observe that $\mathcal{T}$ is an $\ell$-ary tree. For every site $z$ in $\mathcal{T}$ we may look at the subtree $\mathcal{T}_z$ containing $z$, its left children and all of their descendants. The number of walkers whose initial position lie in $\mathcal{T}_z$ to reach $z$ for the first time at some time $t$, denoted by $Z_z(t)$, can be shown to have a Poisson distribution with parameter at least $c\lambda$. Moreover, for different times we have independence, by Poisson thinning. Moreover, as the trees $\mathcal{T}_z$ are disjoint for different $z$’s in $\mathcal{T}$ we see that $Z_z := (Z_z(t) : t \in \mathbb{Z}_+)$ are independent for different $z$’s. (This follows from the requirement that the initial position of the walker is in $\mathcal{T}_z$.)

Now, one scenario in which $u$ is occupied at time $2t$ by a walker belonging at time $2t$ to the friend cluster some walker in $W_u$ is that for some path $(u_0 = u, u_1, \ldots, u_t)$ in $\mathcal{T}$ we have that for all $i \in \{0, \ldots, t-1\}$, $Z_{u_{i+1}}(i) > 0$ and one of the corresponding walkers moved from $u_i$ to $u_{i+1}$ at time $i+1$, while for all $i \in \{1, \ldots, t\}$, $Z_{u_i}(2t - i) > 0$ and one of the corresponding walkers moved from $u_i$ to $u_{i-1}$ at time $2t - i + 1$.

As on each edge $\{u_i, u_{i+1}\}$ we have two independent requirements, each occurring w.p. at least $P[\text{Pois}(c\lambda/(d+1)) > 0]$, we get that if $\lambda \geq C \sqrt{d}$ for some sufficiently large $C$, then we can lower-bound the probability that such a path $(u_0 = u, u_1, \ldots, u_t)$ as in the previous paragraph exists in $\mathcal{T}$, by the probability of the event that the cluster of $u$ in a bernoulli bond percolation on $\mathcal{T}$ (which is an $\ell$-ary tree) with parameter, say $2/(\ell - 1)$, contains some vertex at distance $t$ from $u$. This probability is at least the probability that $u$ is in an infinite open cluster, which is positive.

The difficulty is that we seek to argue that with positive this happens for infinitely many $t$’s. However, this strengthening of the previous conclusion requires only a few simple observations concerning bernoulli percolation on trees, which we defer for the proof of Theorem 2.

Proof of Theorem 2. The lower bound on $\lambda_0$ follows from Theorem 8.1 and the fact that the spectral radius of SRW on $T_d$ is $\rho(T_d) = \frac{2\sqrt{d-1}}{d}$ (cf. [11, Theorem 6.10]) and so by (2.5) the
spectral radius of LSRW with holding probability $1/(d+1)$ on $T_d$ is $\frac{1}{d+1} + \frac{d}{d+1} \frac{2\sqrt{d-1}}{d}$. We now prove the upper bound. By Theorem 5.1 we may assume that $d \geq 4$. Fix some $u, v \in V$. We shall show that if $\lambda \geq C\sqrt{d}$ for some absolute constant $C$ to be determined later, then $P_\lambda[FC(u) = FC(v) \mid u, v \in \Xi] > c_1$ for some constant $c_1 = c_1(d) > 0$ independent of $(u, v)$.

Throughout the proof we condition on the event that $u, v \in \Xi$. We now set $u$ to be the root of $T_d$. This induces a partial order $\leq$, where $a \leq b$ iff the path from $b$ to $u$ goes through $a$. The children of $a \in V$ are $\{b : d(a, b) = 1, a \leq b\} = \{b \sim a : d(b, u) = d(a, u) + 1\}$ (where $d(\bullet, \bullet)$ is the graph distance). Denote $\ell := [(d - 1)/2]$.

For each $a \in V$ we distinguish between its $\ell$ leftmost children, denoted by $L_a$, and its $d - \ell - 1$ rightmost children $R_a$ (apart from $a = u$, for which $R_u$ is taken to be the $d - \ell$ rightmost children of $u$). Let $\mathcal{R}$ be the collection of all vertices such that the path between them and $u$ is contained in $\{u\} \cup (\cup_{a \in V} R_a)$. By symmetry, we may assume that $v \in \mathcal{R}$.

For each $a \in \mathcal{R}$ we denote by $T_{a, L}$ the tree rooted at $a$ with vertex set

$$V_a := \{a\} \cup (\cup_{b' \in L_a} \{b' : b' \leq b\})$$

(where $T_{a, L}$ is the induced graph on this set; in other words, this is the tree containing $a$ and its left children, along with all of their descendants). For each $a \in \mathcal{R}$ and $t \geq 1$ let $W_{a, L}(t)$ be the set of walkers whose initial position is in $V_a \setminus \{a\}$ that reached $a$ for the first time at time $t$. Set $W_{a, L}(0) := W_a$. For $a \in \mathcal{R}$ and $b \sim a$ let $W_{(a, b), L}(t)$ be the set of walkers in $W_{a, L}(t)$ whose location at time $t + 1$ is $b$ (i.e., this is the set of walkers whose initial position is in $V_a \setminus \{a\}$, who reached $a$ for the first time at time $t$ and moved to $b$ in their next step). As $T_{a, L}$ and $T_{a', L}$ are disjoint for all $a \neq a' \in \mathcal{R}$ we have that $(\mathcal{W}_{(a, b), L}(t))_{a, b, t : a \in \mathcal{R}, b \sim a, t \in \mathbb{Z}_+}$ are disjoint. Hence by Poisson thinning the following holds:

1. $(\mathcal{W}_{(a, b), L}(t))_{a, b, t : a \in \mathcal{R}, b \sim a, t \in \mathbb{Z}_+}$ are independent and for each fixed $t$, we have that $(\mathcal{W}_{(a, b), L}(t))_{a, b, a \in \mathcal{R}, b \sim a}$ are i.i.d. Pois($\alpha_t$), where by reversibility (used in the second equality)

$$\alpha_t(d + 1)/\lambda = \sum_{b \in V_a} \mathbb{P}_b(T_a = t) = \mathbb{P}_a(S_1, \ldots, S_t \in V_a \setminus \{a\}),$$

where $(S_k)_{k \geq 0}$ is a LSRW (with holding probability $\frac{1}{d+1}$), $T_a := \inf\{s : S_s = a\}$ is the hitting time of $a$ and $\mathbb{P}_b$ denotes the law of a LSRW (with holding probability $\frac{1}{d+1}$) started from $b$.

Thus if $C$ is taken to be sufficiently large we get that

$$\alpha_t \geq \frac{\lambda}{d+1}\mathbb{P}_a(\{S_k : k \geq 1\} \subseteq V_a \setminus \{a\}) > \log \left(1 - \frac{2}{\sqrt{d - \ell - 1}}\right), \quad (6.1)$$

where we have used the fact that $\mathbb{P}_a(\{S_k : k \geq 1\} \subseteq V_a \setminus \{a\})$ is bounded from below, uniformly in $d$ and that $\ell = [(d - 1)/2]$ and so $|\log \left(1 - \frac{2}{\sqrt{d - \ell - 1}}\right)| \leq C_0/\sqrt{d}$. 

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Denote by $T_u = (U_u, E_u)$ and $T_v = (U_v, E_v)$ the induced graphs on
\[
U_u := \{a \in \mathcal{R} : v < a\} \quad \text{and} \quad U_v := \{a \in \mathcal{R} : v \leq a\},
\]
respectively. Crucially, by construction, $U_u$ and $U_v$ are disjoint.

For each $s \geq 0$, $a \in \mathcal{R}$ and $a' \sim a$ we denote by $J_{(a,a')}(s)$ the indicator of $|W_{(a,a'),L}(s)| > 0$.

Note that by (6.1) $p := \inf_{t>0} (1 - e^{-\alpha t}) \geq 2/\sqrt{d - \ell - 1}$. (6.3)

By (1) we have that

(2) The joint distribution of $(J_{(a,a'),s})_{a,a',s:a\in\mathcal{R},a'\sim a,s\geq 0}$ stochastically dominates that of independent Bernoulli($p$) random variables.

We say that $u$ (respectively, $v$) is good at time $2t$ if there exists some path $(\gamma_0 = u, \gamma_1, \ldots, \gamma_t)$ in $T_u$ (respectively, $(\gamma_0 = v, \gamma_1, \ldots, \gamma_t)$ in $T_v$) such that both $J_{(\gamma_i,\gamma_{i+1})}(i) = 1$ and $J_{(\gamma_{i+1},\gamma_i)}(2t - i - 1) = 1$, for all $0 \leq i \leq t - 1$. We denote the indicator of $u$ (respectively, $v$) being good at time $2t$ by $Z_u(2t)$ (respectively, $Z_v(2t)$). Note that if $u$ (respectively, $v$) is good at time $2t$ then there is some walker $w \in FC_{2t}(u)$ (respectively, $FC_{2t}(v)$) which reached $u$ (respectively, $v$) for the first time at time $2t$. Thus on the event that both $u$ and $v$ are good (simultaneously) for infinitely many even times, we get that $a_s FC(u) = FC(v)$. Hence in order to conclude the proof, it suffices to show that $u$ and $v$ are good (simultaneously) for infinitely many even times with probability at least $q > 0$, for some $q$ independent of $u, v$. We do so by comparison with super-critical bernoulli bond percolation (on $T_u$ and $T_v$) which we now define.

Bernoulli bond percolation on a graph $H = (U, F)$ with density $q$ is a random graph $H_q := (U, F_q)$ such that $F_q \subseteq F$ is defined by including in it every edge $f \in F$ independently w.p. $q$. Let

\[ p_c(H) := \inf \{q : H_q has an infinite connected component with positive probability\} \]

be the critical density for bernoulli bond percolation on $H$. Then
\[ p_c(T_u) = 1/(d - \ell - 1) = p_c(T_v). \]

Moreover, for all $q > p_c(T_u)$ we have that a.s. $(T_u)_q$ satisfies that
\[ p_c((T_u)_q) = p_c(T_u)/q = p_c((T_v)_q) \]
(where $(T_u)_q$ is the graph obtained from Bernoulli bond percolation with density $q$ on $T_u$).

In fact, for every $q > \sqrt{p_c(T_u)}$ we have that

(3) The connected component $C_{(T_u)_q}(u)$ of $u$ in $(T_u)_q$ is infinite with positive probability.
is independent of the event that $\tilde{\beta}, \tilde{\delta} > 0$.

We say that $\tilde{\beta}$, $\tilde{\delta} > 0$ least

By (7)-(8), conditioned on $\tilde{T}$, the graph $(\mathcal{T}_u)_q$ satisfies that $|C_T(u)| = \infty$ w.p. at least $\tilde{\delta}$, conditioned on $(\mathcal{T}_u)_q$. The same applies for $\mathcal{T}_v$ (with $v$ in the role of $u$ above). Note that by (6.3)

$$p > \sqrt{p_c(\mathcal{T}_u)}.$$ 

(6.4)

Let $b \in U_u$ (respectively, $\in U_v$) and $b' \in R_b$, where $U_u$ and $U_v$ are as in (6.2). Denote the distance of $b$ from $u$ (respectively, $v$) by $r$. We say that the edge $\{b, b'\}$ is forward good if $J(b,b')(r) = 1$ and that it is backwards good for time $2t$ (for $t > r$) if $J(b,b)(2t - r - 1) = 1$.

This gives raise to the following random subgraphs of $\mathcal{T}_u = (U_u, E_u)$ and $\mathcal{T}_v = (U_v, E_v)$:

Let $\tilde{T}_u$ (respectively, $\tilde{T}_v$) be a graph with vertex set $U_u$ (respectively, $U_v$) and edge set

$$\tilde{E}_u := \{e \in E_u : e \text{ is forward good}\} \quad \text{(resp. } \tilde{E}_v := \{e \in E_v : e \text{ is forward good}\}).$$

Let $\tilde{T}_{u,t} := (U_u, \tilde{E}_{u,t})$ be the random subgraph of $\tilde{T}_u$, defined by setting $\tilde{E}_{u,t}$ to be the collection of all $e \in E_{u,t}$ which are backwards good for time $2t$, where $E_{u,t}$ is the set of edges in $\mathcal{T}_u$ having both end-points within distance $t$ from $u$. Define $\tilde{T}_{v,t} := (U_v, \tilde{E}_{u,t})$ in an analogous manner. Note that:

(6) $\tilde{T}_u$ and $\tilde{T}_u$ are independent (as $U_v \cap U_v = \emptyset$) and (by (2)) $\tilde{T}_u$ (respectively, $\tilde{T}_v$) stochastically dominates bernoulli bond percolation on $\mathcal{T}_u$ (respectively, $\mathcal{T}_v$) with parameter $p$, where $p$ is as in (6.3).

(7) The collection of random forests $(\tilde{T}_{u,t})_{w:t\in\{u,v\},t\geq 1}$ are conditionally mutually independent, given $(\tilde{T}_u, \tilde{T}_v)$ (this follows from (2)).

(8) Given $\tilde{E}_u \cap E_{u,t}$, the joint law of $(1_{e \in \tilde{E}_{u,t}})_{e \in \tilde{E}_u \cap E_{u,t}}$ stochastically dominates that of i.i.d. Bernoulli $p$ random variables, where $p$ is as in (6.3) (this follows from (2)).

We say that $\tilde{T}_u$ (respectively, $\tilde{T}_v$) is $\delta$-excellent if the connected component of $u$ (respectively, $v$) in $\tilde{T}_u$ (respectively, $\tilde{T}_v$) is infinite and the probability that the connected component of $u$ (respectively, $v$) in a Bernoulli bond percolation on $\tilde{T}_u$ (respectively, $\tilde{T}_v$) with parameter $p$ is infinite is at least $\delta$. Note that by (6), the event that $\tilde{T}_u$ is $\delta$-excellent is independent of the event that $\tilde{T}_v$ is $\delta$-excellent. By (3)-(6) and (6.4) there exist some $\beta, \delta > 0$ (independent of $(u, v)$) so that $\tilde{T}_u$ and $\tilde{T}_v$ are both $\delta$-excellent with probability at least $\beta$.

By (7)-(8), conditioned on $\tilde{T}_u$ and $\tilde{T}_v$ both being $\delta$-excellent, the conditional joint distribution of $(Z_{w}(2t))_{w:t \in \{u,v\}, t \geq 0}$ stochastically dominates that of i.i.d. Bernoulli$(\delta)$ r.v.’s, and
so by the Borel-Cantelli Lemma indeed a.s. \( Z_u(2t) = 1 = Z_v(2t) \) for infinitely many \( t \)'s, as desired.

Indeed, by (7) it suffices to show that \( P_\lambda[Z_w(2t) = 1 \mid \tilde{T}_w \text{ is } \delta\text{-excellent}] \geq \delta \), for each \( w \in \{u, v\} \) and \( t > 0 \). By (8), for each fixed \( t \), (given \( \tilde{T}_u \)) the (conditional) probability that \( u \) is connected in \( \tilde{T}_{u,t} \) to some vertex of distance \( t \) from it (i.e., that \( Z_u(2t) = 1 \)) is at least the probability that the connected component of \( u \) in \( (\tilde{T}_u)_p \) is infinite, which by definition of the notion of \( \delta \)-excellence is at least \( \delta \), given that \( \tilde{T}_u \) is \( \delta \)-excellent (an analogous statement holds for \( v \)).

\[ \square \]

7 Proof of Theorem 3

Before turning to the proof of Theorem 3 let us explain our strategy. Consider the following naive exploration process. Expose the first \( t \) steps of some walker \( w \in \mathcal{W}_v \) for some \( v \in V \). Let \( G_1 \) be the set of walkers that \( w \) met by time \( t \). Pick \( t = t(\lambda, \rho) \) so that the expectation of \( |G_1| \) is at least some large constant \( L \) (uniformly in \( v \)). Then sequentially expose the first \( t \) steps of the walks performed by the walkers in \( G_1 \) and let \( G_2 \) be the collection of walkers not in \( G_1 \cup \{w\} \) which met some walker from \( G_1 \) by time \( t \). Inductively, let \( G_{k+1} \) be the collection of walkers not in \( (\bigcup_{i=1}^{k} G_i) \cup \{w\} \) which met some walker from \( G_k \) by time \( t \).

The problem with this naive approach is that it is not clear that for large \( k \), “typically”: for \( w' \in G_k \) (or even for at least some fixed small fraction of \( w' \in G_k \)) we have that the expectation of the contribution of \( w' \) to \( |G_{k+1}| \) is large, because the contribution is restricted to walkers not in \( (\bigcup_{i=1}^{k} G_i) \cup \{w\} \) (plus we need to avoid double-counting contributions of different walkers in \( G_k \), corresponding to the case that two or more walkers in \( G_k \) discover the same walker). However, as follows from our analysis below, if \( \rho \) is sufficiently small (some precise version of) the statement of the previous sentence indeed holds.

Below we consider “\( s \)-walks” (defined by looking at a walk only at times which are multiples of \( s \) for some sufficiently large \( s = s(\rho) \)) in order to obtain walks with sufficiently small spectral radius. Instead of the aforementioned naive aforementioned exploration process, we work with a variant of an exploration process due to Benjamini, Nachmias and Peres [5] which allows us to perform effectively the bookkeeping of which “active but still unchecked” walkers (i.e., walkers already recruited to the exploration process, such that the \( s \)-walk performed by them is yet unexposed) are likely to recruit “many” new walkers to the exploration process.

\[ \text{Proof.} \] Recall that \( t_{C,\lambda} := \left\lceil \frac{C}{\lambda(1-\rho)} \right\rceil \), where \( \rho \) is the spectral radius of LSRW on \( G = (V, E) \). Fix some \( v \in V \). By a standard use of Kolmogorov’s 0-1 law, it suffices to show that \( P_\lambda[|\mathcal{FC}_{t_{C,\lambda}}(v)| = \infty] > 0 \), provided that \( C \) is sufficiently large. In particular, we may condition on \( v \in \Xi \). Denote

\[ s := \left\lceil 8K/(1-\rho) \right\rceil \quad \text{and} \quad M := \left\lceil 32K/\lambda \right\rceil, \quad \text{where } K \geq 3 \]
shall be determined later. Consider the random walk obtained by replacing the transition kernel $P$ by $Q := P^s$ (i.e., every step of this walk is $s$ steps of the original LSRW). We refer to such walks as $s$-walks and denote it by $(S_t^{(s)})_{t \geq 0}$ and the corresponding probability measure (for initial state $u$) by $P_u^{(s)}$ (similarly, when the initial distribution of the walk is $\mu$ we write $P_\mu^{(s)}$).

Our strategy is to expose a subset of $\text{FC}_{sM}(v)$ via a variant of an exploration process due to Benjamini, Nachmias and Peres [5]. Recall that $\mathcal{W}_u(t)$ is the set of walkers which are at vertex $u$ at time $t$. Our exploration process produces increasing sets of space-time coordinates $\{A_\ell\}_{\ell \geq 0}$, which are subsets of $V \times \{st : 0 \leq t \leq M\}$ so that for all $\ell$ and all $(u, st) \in A_\ell$ we have that $\mathcal{W}_u(st) \subseteq \text{FC}_{sM}(v)$. Start with $A_0 := \{(v, 0)\}$. We proceed by exposing the first $sM$ steps of the walk $(w_v(i))_{0 \leq i \leq sM}$ performed by some walker in $\mathcal{W}_v$ and set

$$A_1 := \{(w_v(ts), ts) : 0 \leq t \leq M, w_v(ts) \notin \{w_v(t's) : t' < t\}\}$$

(in simple words, these are the space time co-ordinates of the first $M$ steps of the corresponding $s$-walk, after we omit repetitions in the space co-ordinate), $C_1 := \{(v, 0)\}$ and $U_1 := A_1 \setminus C_1$. We will construct inductively sets $U_\ell, C_\ell, A_\ell := U_\ell \cup C_\ell$ and

$$A_\ell := \{u : (u, st) \in A_\ell \text{ for some } t\}$$ (7.1)

such that $A_1 \subseteq A_2 \subseteq \cdots$. To avoid double-counting (which may arise since $\mathcal{W}_u(st)$ and $\mathcal{W}_w(st')$ need not be disjoint), we consider certain subsets of the $\mathcal{W}_u(st)$'s. Set

$$\mathcal{W}_u^\ell(st) := \mathcal{W}_u(st) \setminus \bigcup_{a \in A_\ell, t' \in \mathbb{Z}_+ : (a, t') \neq (u, t)} \mathcal{W}_a(st').$$ (7.2)

That is $\mathcal{W}_u^\ell(st)$ is the collection of walkers occupying $u$ at time $st$ which avoid $A_\ell$ throughout their $s$-walks, apart from at time $t$ of the $s$-walk (that is, they did not visit any $a \in A_\ell$ at any time in $s\mathbb{Z}_+ \setminus \{st\}$, where $s\mathbb{Z}_+ := \{sz : z \in \mathbb{Z}_+\}$).

From the construction below it will be clear that for all $\ell$

$$|A_\ell| = |A_\ell| \quad \text{and} \quad |C_\ell| = \ell.$$-

At each stage $\ell$ some of $(u, st) \in A_\ell$ will be checked, $C_\ell$, and some unchecked, $U_\ell$. As long as $U_\ell$ is non-empty we can proceed with the $(\ell + 1)$-th stage, in which we pick some $(u, st) \in U_\ell$ (the manner in which we choose $(u, st)$ shall be described later) and first expose $|\mathcal{W}_u^\ell(st)|$ and set $C_{\ell+1} := C_\ell \cup \{(u, st)\}$. If $|\mathcal{W}_u^\ell(st)| = 0$ we set $U_{\ell+1} := U_\ell \setminus \{(u, st)\}$. Otherwise, we pick one walker $w$ from $\mathcal{W}_u^\ell(st)$ and expose its walk by time $sM$, $(w(i))_{0 \leq i \leq sM}$ and set

$$U_{\ell+1} := (U_\ell \cup \{(w(is), is) : 0 \leq i \leq M, i \neq t, w(is) \notin \{w(js) : j < i\}\}) \setminus \{(u, st)\}$$

(in simple words, we add to $U_\ell$ some of the space time co-ordinates of the first $M$ steps of the $s$-walk of $w$, where we avoid taking more than one pair with the same space co-ordinate,
To motivate what comes, assume for the moment that we can pick \((u, st)\) and then subtract from it \(\{w\}\). From the analysis below and Poisson thinning, it follows that for such \((u, st)\) we have that

\[
P^{(s)}[\forall t' \neq t, S^{(s)}_{t'} \notin A_t \mid S^{(s)}_t = u] \geq 1 - 2e^{-4K}. \tag{7.3}
\]

From the analysis below and Poisson thinning, it follows that for such \((u, st)\) we have that

\[
|W^\ell_u(st)| > 0 \text{ w.p. at least } q := 1 - \exp[-\lambda(1 - 2e^{-4K})]\text{ and}
\]

\[
\mathbb{E}[|U_{t+1}| - |U_t| \mid A_t, |W^\ell_u(st)|] \geq M/4 \text{ on the event } |W^\ell_u(st)| > 0
\]

(it equals \(-1\) on the complement). As \(\lambda \in (0,1)\), provided that \(K\) is sufficiently large, in such stage

\[
\mathbb{E}[|U_{t+1}| - |U_t|] \geq qM/4 - (1 - q) \geq 8qK/\lambda - 1 \geq 4K.
\]

If we could always pick such \((u, st)\), then it is intuitively clear that with positive probability \(|A_\ell| \geq 2\ell\) for all \(\ell\) and thus the construction will have infinitely many stages, implying the desired result. As we now explain, at least a \((1 - e^{-4K})\)-fraction of \((u, st) \in A_t\) satisfy (7.3), and thus as long as \(|A_\ell| \geq 2\ell\), we will indeed be able to choose \((u, st) \in U_t\) satisfying (7.3).

Following [5], given some \(A \subseteq V\) and \(\alpha \in (0,1)\) we say that \(a \in V\) is \((A, \alpha)\)-good if

\[
P^{(s)}_a[T^+_A < \infty] \leq \alpha, \text{ where } T^+_A := \inf\{t > 0 : S^{(s)}_t \in A\}.
\]

Denote the uniform distribution on \(A\) by \(\pi_A\). As the spectral radius of \(Q = P^s\) is \(\rho^s \leq e^{-8K}\), it follows from Lemma 2.1 in [5] that for every finite \(A \subseteq V\)

\[
P^{(s)}_a[T^+_A < \infty] \leq \rho^s \leq e^{-8K}. \tag{7.4}
\]

It follows from (7.4) that for every finite \(A \subseteq V\), the set

\[
G_A := \{a \in A : a \text{ is } (A, e^{-4K})\text{-good}\}
\]

satisfies that

\[
|G_A|/|A| \geq 1 - e^{-4K}. \tag{7.5}
\]

Fix some \(a \in G_A\) and \(k \leq M\). Let

\[
W_a(A, ks) := W_a(ks) \setminus \cup_{\ell \in \mathbb{Z}_+, a' \in A : (\ell, a') \neq (k, a)} W_{a'}(\ell s)
\]

be the collection of walkers which are at vertex \(a\) at time \(ks\), which avoid \(A\) throughout their \(s\)-walks, apart from at time \(ks\) (time \(k\) of their \(s\)-walk). Note that when we take \(A = A_t\) and \(a \in A_t\), we have that \(W_a(A, ks) = W^\ell_u(ks)\) (where \(A_t\) and \(W^\ell_u(ks)\) are as in (7.1)-(7.2)). This allows us to translate the conclusion below into one concerning (7.3).

Observe that by reversibility if \(a \in G_A\) and \((w(t))_{t \geq 0}\) is the walk performed by some walker \(w \in W_a(A, ks)\), then the walks \((w_{\text{forward}}(t))_{t \in \mathbb{Z}_+} := (w((k+t)s))_{t \in \mathbb{Z}_+}\) and \((w_{\text{backward}}(t))_{0 \leq t \leq k} := (w((k-t)s))_{0 \leq t \leq k}\) are (independent) \(s\)-walks conditioned to avoid \(A\), apart from at time
0. In particular, (7.3) holds for \( A \) in the role of \( A_\ell \) as \( a \in G_A \). Again using \( a \in G_A \) we have that
\[
\mathbb{E}[|W_a(A, ks)|] \geq \mathbb{E}[|W_a(ks)|](1 - 2P^{(s)}_a[|T^+_A| < \infty]) \\
\geq (1 - 2e^{-4K})\mathbb{E}[|W_a(ks)|] = \lambda(1 - 2e^{-4K}).
\]
By Poisson thinning if \( a \in G_A \), then for all \( k \) we have that \( |W_a(A, ks)| \) has a Poisson distribution with mean at least \( \lambda(1 - 2e^{-4K}) \).

Using (2.4) it is not hard to show that the expected number of times an \( s \)-walk of length at most \( M \) intersects itself is at most \( M\rho^*/(1 - \rho^*) \leq \frac{9}{10}Me^{-8K} \leq e^{-4K}/\lambda \), provided that \( K \) is sufficiently large. Thus by Markov’s inequality, if \( a \in G_A \) and \((w(t))_{t \geq 0} \) is the walk performed by some walker \( w \in W_a(A, ks) \) for some \( k \leq M \), then \((w(t))_{t:0 \leq t \leq M, t \neq k} \) visits at least \( M/4 \geq 2K/\lambda \) distinct vertices with probability at least \( p := 1 - \frac{1}{Ke^{4K}(1-2e^{-4K})} \).

Let
\[
U_\ell := \{u : (u, st) \in U_\ell \text{ for some } t \} \quad \text{and} \quad C_\ell := \{u : (u, st) \in C_\ell \text{ for some } t \}.
\]
Assume that \(|A_\ell| \geq 2\ell\). Then \(|G_{A_\ell}| \geq (1 - e^{-4K})2\ell > \ell \) and so \( G_{A_\ell} \setminus C_\ell = G_{A_\ell} \cap U_\ell \) is non-empty (as \(|C_\ell| = \ell|\)). As long as this is the case, in the \( \ell \)-th stage we expose some \((u, st) \in U_\ell \) such that \( u \in G_{A_\ell} \cap U_\ell \), where the choice of \((u, st)\) is made according to some prescribed order on \( V \times \mathbb{Z}_+ \) (or simply according to the lexicographic order on the stage in which the walkers were discovered and their time coordinate). By the above analysis, provided that \( K \) is sufficiently large, the probability that \(|A_{\ell+1}| - |A_\ell| \geq 2K/\lambda \) is at least \( qp = (1 - \exp[-\lambda(1 - 2e^{-4K})]) \times (1 - \frac{1}{Ke^{4K}(1-2e^{-4K})}) \geq \lambda/2 \) (for \( \lambda \leq 1 \) and large \( K \)), and so
\[
\mathbb{E}[|A_{\ell+1}| - |A_\ell| \mid |A_\ell| \geq 2\ell] \geq (2K/\lambda)pq \geq K \geq 3.
\]
Combining this with Azuma inequality (applied to the Doob’s martingale of \(|A_\ell|_{\ell \geq 0}\)), it is not hard to verify that with positive probability \(|A_\ell| \geq 2\ell \) for all \( \ell \) (cf. the proof of Theorem 1.1 in [5]) as desired.

8 A lower bound on \( \lambda_c \) in the non-amenable case

**Theorem 8.1.** Let \( G = (V, E) \) be an infinite connected non-amenable regular graph. Denote the spectral radius of LSRW on \( G \) (with an arbitrary holding probability \( p \)) by \( p \). Then the SN model on \( G \) with holding probability \( p \) satisfies
\[
P_{\lambda}[\text{Con}] = 0, \quad \text{for all } \lambda < \frac{1}{2} \left( \rho^{-1} - 1 \right).
\]

[3] The term \( 1 - 2e^{-4K} \) in the denominator is there since instead of taking \( w \in W_a(ks) \) we take \( w \in W_a(A, ks) \), which means that the law of its walk is conditioned to be in some set of walks whose probability (w.r.t. the law of a walk of a walker in \( W_a(ks) \)) is at least \( 1 - 2e^{-4K} \).
Throughout the section we fix the holding probability of the walks to be some constant $0 \leq p < 1$. Let $\mu_\lambda$ (respectively, $\nu_\lambda$) be the distribution of $1 + 2X_\lambda$ (respectively, $1 + X_\lambda$), where $X_\lambda \sim \text{Pois}(\lambda)$. A lazy branching random walk on $G$ with offspring distribution $\mu_\lambda$ started at a vertex $o$, denoted by $\text{LBRW}(\mu_\lambda, o)$, is defined as follows. At time 0 there are a random number of particles distributed according to $\nu_\lambda$ which are all positioned at vertex $o$. Call the set of these particles generation number 0. The process is then defined inductively. At stage $t$ each particle $w$ belonging to the $t$-th generation performs one step of $\text{LSRW}$ on $G$ from its position at time $t$, where steps performed by different particles are independent. Then it gives birth to a random number of particles (referred to as its offsprings) $Y_w \sim \mu_\lambda$, at its current position, independently of all other particles. The set of all the offspring of the particles from the $t$-th generation is defined to be the $(t + 1)$-th generation.

The following interpretation of $\text{LBRW}(\mu_\lambda, o)$ is useful for our purposes. First, by including the previous generations as part of the current generation, we may think of the offspring distribution as being the same as that of $2X_\lambda$, where $X_\lambda \sim \text{Pois}(\lambda)$. Equivalently, in this interpretation, a particle does not “die” after giving birth to some offspring at a certain step, and may give birth to additional offspring in future stages (alternatively, we may view the particle as an “offspring of itself”).

We may think of each particle as giving birth to $\text{Pois}(\lambda)$ “regular particles” which then clone themselves. By reversibility, we may think of the regular particles as performing independent $\text{LSRW}$s, while the clones perform a $\text{LSRW}$ moving backwards in time in the following sense. The law of $\text{LSRW}$ started from $v$ is the same as the law of $(Y_s)_{s=0}^\infty$, where $Y_s := X_{-s}$ for all $s \geq 0$ and $(X_s)_{s \in \mathbb{Z}}$ is a bi-infinite $\text{LSRW}$ conditioned on being at $v$ at time 0. Hence we may assume the walk of the clone particle is sampled in that manner.

We now describe a process which, based on the previous two observations, is essentially equivalent to $\text{LBRW}(\mu_\lambda, o)$. In particular, the expected total number of visits to each vertex (including multiplicities) is the same for the two processes. While the definition of this process is somewhat cumbersome, it will be transparent that this process stochastically dominates the exploration process used below in order to “expose” $\text{FC}(\omega)$, the friend cluster of $\mathcal{V}_o$. We intentionally use similar notation to describe this variant of $\text{LBRW}(\mu_\lambda, o)$ as the one used later in the exploration process of $\text{FC}(\omega)$.

In the 0-th generation, $\mathcal{V}_{0,0}$, we start with $1 + \text{Pois}(\lambda)$ walkers $v_{0,0,1}, \ldots, v_{0,0,|\mathcal{V}_{0,0}|}$ at $o$. Let each $v_{0,0,j}$ perform a $\mathbb{Z}$-indexed (bi-infinite) random walk $(v_{0,0,j}(t))_{t \in \mathbb{Z}}$ on $G$, conditioned to be at $o$ at time 0. Such a walk can be sampled by taking two independent $\mathbb{Z}_+$-indexed walks started at $v$, $(fv_{0,0,j}(t))_{t \geq 0}$ and $(bv_{0,0,j}(t))_{t \geq 0}$ (which can be thought of as 2 independent walks performed by 2 separate particles) and concatenating one to the reversal of the other as follows $v_{0,0,j}(t) := fv_{0,0,j}(t)$ and $v_{0,0,j}(-t) := bv_{0,0,j}(t)$ for all $t \geq 0$.

In the first stage we expose $v_{0,0,j}(\pm 1)$ for all $j$ (in the above interpretation, we expose one step of the walk of the forward particle $fv_{0,0,j}(1)$ and one of the backward particle $bv_{0,0,j}(1)$) and plant at $v_{0,0,j}(\pm 1)$ (independently for different $j$’s and for $\pm 1$) $\text{Pois}(\lambda)$ walkers performing (independent) $\mathbb{Z}$-indexed random walks on $G$ conditioned to be at
\( v_{0,0}(\pm 1) \) at time \( \pm 1 \), respectively. Denote the set of walkers planted at stage 1 at time \( \pm 1 \) by \( \mathcal{V}_{1,\pm 1} = \{v_{1,\pm 1,1}, \ldots, v_{1,\pm 1,|\mathcal{V}_{1,\pm 1}|}\} \), respectively. The construction continues inductively as follows:

By the end of stage \( r \), for all \( 0 \leq i \leq r \) and \( -i \leq j \leq i \) such that \( i - j \) is even, we have already defined \( \mathcal{V}_{i,j} = \{v_{i,j,1}, \ldots, v_{i,j,|\mathcal{V}_{i,j}|}\} \) the set of walkers planted at stage \( i \) and time \( j \), and for all \( 1 \leq k \leq |\mathcal{V}_{i,j}| \) exposed \( (v_{i,j,k}(t))_{t\in[|\mathcal{V}_{i,j}|]} \) exposed walker \( k \)-th walker in \( \mathcal{V}_{i,j} \) and \( (v_{i,j,k}(t))_{t\in\mathbb{Z}} \) is the walk she performs. In the \( (r+1) \)-th stage we expose for all \( i, j, k \) as before \( v_{i,j,k}(j \pm (r+1-i)) \) and plant at \( v_{i,j,k}(j \pm (r+1-i)) \) (independently for different \((i, j, k)\)'s and for \( j \pm (r+1-i) \)) \( \text{Pois}(\lambda) \) walkers performing (independent) \( \mathbb{Z} \)-labeled random walks on \( G \) conditioned to be at \( v_{i,j,k}(j \pm (r+1-i)) \) at time \( j \pm (r+1-i) \), respectively. Finally, we denote the set of walkers planted at stage \( r+1 \) at time \( \ell \) by \( \mathcal{V}_{r+1,\ell} = \{v_{r+1,\ell,1}, \ldots, v_{r+1,\ell,|\mathcal{V}_{r+1,\ell}|}\} \).

Below we expose FC(o) in “slow motion” using an exploration process. At each stage \( t \) of the exploration process, new walkers are “recruited” to the friend cluster by meeting at some time \( s \leq t \) walkers already belonging to the exploration process. The walkers recruited at stage \( t \) can be thought of as the \( t \)-th generation of the exploration process.

Let \( \omega \) be some walker in the \( t \)-th generation of the exploration process who was recruited at stage \( t \) due to an acquaintance which occurred at time \( s \) (the set of such walkers shall be denoted below by \( \mathcal{W}_{t,s} \)). Instead of exposing in the \( (t+1) \)-th stage the entire trajectory of \( \omega \), we expose its position at times \( s+1 \) and \( s-1 \). At stage \( t+2 \) we expose its position at times \( s+2 \) and \( s-2 \) (if \( s \geq 2 \)), and so on (at stage \( t+i \) we expose its position at time \( s+i \) and if \( s \geq i \) also at time \( s-i \)).

Let \( (\omega(n))_{n \geq 0} \) be the infinite walk performed by \( \omega \). We can think of \( \omega \) as two separate particles, one a forward particle performing the forward walk \( (\omega(t+n))_{n \geq 0} \) and the other a clone performing the reversed walk \( (\omega(t-n))_{n \geq 0} \). At each stage, for every previously exposed walker \( \omega \) we expose one step of its forward walk and one step of its reversed walk (or in the above terminology, one step of the walk performed by its clone), if it was not fully exposed already. The particle (or clone) recruits new walks if she meets them at the space-time coordinate of her walk which was exposed at the current stage, and if those walkers avoided all the space-time coordinates previously exposed by the exploration process (otherwise these walkers would have already been recruited to the exploration process).

Using Poisson thinning, we can dominate this exploration process by the equivalent formulation of \( \text{LBWR}(\mu, o) \), involving the \( \mathbb{Z} \)-valued walks and the sets \( \mathcal{V}_{t,s} \). Indeed there are two differences between the two. The first is that in the latter the walks of the particles moving backwards in time continue all the way to time \( -\infty \) instead of stopping at time \( 0 \). The second difference is that in the exploration process of FC(o) each particle can only recruit “new” walkers (and their clones), which means that these walkers have to avoid certain space-time coordinates previously exposed by the exploration process. Thus, by Poisson thinning her offspring (= new walkers recruited by her at each stage and their clones) distribution is stochastically dominated by the \( 2\text{Pois}(\lambda) \) distribution.
Unfortunately, while the aforementioned stochastic domination is intuitively clear, its proof requires some cumbersome bookkeeping and no much additional insights beyond the ones described in the above intuitive explanation. For this reason we defer the proof of Proposition 8.2 to Appendix 12.

By Lemma 2.4 every vertex is visited infinitely often a.s.. Thus on the event $\text{Con} \cap \{ o \in \Xi \}$ (assuming it has a positive probability) we have that $\text{FC}(o)$ (the friend cluster of $W_o$) is the set of all walkers, and so $o$ is visited by walkers in $\text{FC}(o)$ infinitely often a.s.. Note that if $P_\lambda[\text{Con}] > 0$, then there must be some $o$ such that $P_\lambda[\text{Con} \cap \{ o \in \Xi \}] > 0$, and so the expected number of times in which vertex $o$ is visited by walkers from $\text{FC}(o)$ including multiplicities (here we count also visits made by a walker $w \in \text{FC}(o)$ at time $t$ in which $w \notin \text{FC}_t(o)$, i.e., before the walker $w$ joined the friend cluster of the walkers in $W_o$) is infinite, as on the event $\text{Con} \cap \{ o \in \Xi \}$ the last expectation is simply the expected number of visits to $o$ by all particles (with multiplicities; The number of such visits is a.s. infinite and so this expectation is infinite even on the event $\text{Con} \cap \{ o \in \Xi \}$). Hence the assertion of Theorem 8.1 follows by combining the following proposition and lemma.

**Proposition 8.2** (proof deferred to Appendix 12). Let $X_v$ be the number of times vertex $v$ was visited by a walker from $\text{FC}(o)$ (including multiplicities) when the density of the walkers is taken to be $\lambda$. Let $Y_v$ be the number of times that vertex $v$ was visited by a particle in $\text{LBRW}(\mu_\lambda, o)$ (where if a particle in the lazy branching random walk $\text{LBRW}(\mu_\lambda, o)$ is born at vertex $v$ this also contributes to $Y_v$). Let $\nu_1$ and $\nu_2$ be the laws of $(X_v)_{v \in V}$ and $(Y_v)_{v \in V}$, respectively. Then $\nu_2$ stochastically dominates $\nu_1$.

**Lemma 8.3.** For $v \in V$ and $n \geq 0$, let $Q_n(v)$ be the the number of particles belonging to the $n$-th generation of $\text{LBRW}(\mu_\lambda, o)$ which were born at vertex $v$. Then for all $v$ and $n \geq 1$,

$$
E[Q_n(v)] = (1 + \lambda)(1 + 2\lambda)^{n-1}P^n(o, v) \leq [(1 + 2\lambda)\rho]^{n}.
$$

In particular, if $\lambda < \frac{1}{2}(\rho^{-1} - 1)$ we have that $\sum_{n=0}^{\infty} Q_n(o) < \infty$ a.s..

The proof of the equality in (8.1) is obtained by a simple induction on $n$, performed simultaneously over all vertices (we omit the details). The inequality follows from (2.4).

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9 Appendix A: Proof of the regeneration Lemma & Lemma 2.4

Proof of Lemma 2.3. The independence and the fact that the marginal distributions are Poisson follow from Poisson thinning. Denote \( P(v, A) := \sum_{a \in A} P(v, a) \). By reversibility, \( \mathbb{E}_\lambda[Y_{v,A}(t)] = \lambda P^t(v, A) \) and so

\[
\lambda - \mathbb{E}_\lambda[Y_{v,A}(t)] = \mathbb{E}_\lambda[Y_{v,A}(t)] = \lambda P^t(v, A) \leq C_d \lambda |A| / \sqrt{t},
\]

where we have used the fact that for all \( t \geq 1 \), \( \sup_x P^t(x, x) \leq C_d / \sqrt{t} \) (cf. [10, Theorem 21.18]) and that \( \sup_{x,y} P^t(x, y) \leq \sup_x P^{2t/2}(x, x) \) (see Proposition 9.1 below).

\[
\square
\]

Proposition 9.1. SRW on a regular graph satisfies \( \sup_{x,y} P^t(x, y) \leq \sup_x P^{2\lfloor \frac{t}{2} \rfloor}(x, x) \).

Proof. By reversibility (used in the second equality and to argue that \( \sum_z [P^t(a, z)]^2 = \sum_z P^t(a, z) P^t(z, a) = P^{2t}(a, a) \)) and the Cauchy-Schwartz inequality (first inequality)

\[
P^{2t}(x, y) = \sum_z P^t(x, z) P^t(z, y) \leq \sum_z P^t(x, z) P^t(y, z)
\]

\[
\leq \sqrt{P^{2t}(x, x) P^{2t}(y, y)} \leq \sup_x P^{2t}(x, x).
\]

Similarly, \( P^{2t+1}(x, y) \leq \sqrt{P^{2t+2}(x, x) P^{2t}(y, y)} \leq \sup_x P^{2t}(x, x) \).

\[
\square
\]

Proof of Lemma 2.4. The fact that the distribution of \( N_i(w) \) is Poisson follows from Poisson thinning. Let \( M_t(w) := \sum_{i=1}^t |W_{w_i}(i)| \). By stationarity of the law of the occupation measure (Fact 2.1) we have that \( \mathbb{E}_\lambda[M_t(w)] = \lambda t \). Decomposing the last expectation according to the first time \( i \) at which a walker is at \( w_i \) (and noting that the contribution corresponding to time \( i \) is \( (\mathbb{E}_\lambda[N_i(w)] - \mathbb{E}_\lambda[N_{i-1}(w)]) \sum_{j=0}^{t-i} P^j(w_i, w_{i+j}) \), which can be bounded from above by \( (\mathbb{E}_\lambda[N_i(w)] - \mathbb{E}_\lambda[N_{i-1}(w)]) \sum_{j=0}^t \sup_{x,y \in V} \lambda P^j(x, y) \)) we get that

\[
\lambda t = \mathbb{E}_\lambda[M_t(w)] \leq \mathbb{E}_\lambda[N_t(w)] \sum_{j=0}^t \sup_{x,y \in V} \lambda P^j(x, y) \leq \mathbb{E}_\lambda[N_t(w)] C(d) \sqrt{t}.
\]

\[
\square
\]

10 Appendix B: explicit construction of the SN model

Proof of Proposition 2.2. For every \( v \in V \) let \( M_v(t) \) be a homogeneous Poisson process on \( \mathbb{R}_+ \) with rate 1 (all of which defined on the same probability space so that they are independent). For each \( \lambda > 0 \), when the density of walkers is taken to be \( \lambda \), we take \( |W^\lambda_v| := M_v(\lambda) \), where \( W^\lambda_v \) denotes the the set of walkers whose initial position is \( v \) (in the case of density \( \lambda \)). Thus if \( \lambda_1 < \lambda_2 \) then for all \( v \in V \) we have that \( W^\lambda_1 \subseteq W^\lambda_2 \). The assertion of the Proposition is already clear at this point. For the sake of completeness, we give additional details concerning the construction.
We first establish translation invariance. Let $\lambda$ shall show that there exists a coupling of $AC^{\lambda}$ and $\mathbb{M}$.

Using the notation from Section 2.2, let $w_n(t) = (w_n^u(t))_{t \in \mathbb{Z}_+}$ be a LSRW on $G$, started at $v$ (throughout we denote the law of such a walk by $\mathbb{P}_v$, where the holding probability is either clear from context or irrelevant). We take all the walks to be independent. Moreover, we take $W := (w_n^u)_{n \in \mathbb{N}, u \in V}$ and $\mathbb{M} := (M_v)_{v \in V}$ to be independent. We think of $w_n^u$ as the walk performed by the $n$-th particle whose initial position is $v$.

We are now in the position to define $AC^{\lambda}_t := (V, E_{t, \lambda})$. Denote by $Z_i^{u,v}(t)$ the indicator of the event that the $i$-th particle from $u$ met the $j$-th particle from $v$ by time $t$ (i.e., $Z_i^{u,v}(t) := 1\{w_n^u(s) = w_n^v(s) \text{ for some } s \leq t\}$). We want the last event to imply that $\{u, v\} \in E_{t, \lambda} \text{ iff } i \leq |W^\lambda_u| = M_u(\lambda) \text{ and } j \leq |W^\lambda_v| = M_v(\lambda)$ (because we want the number of particles starting at each site which are involved in the dynamics to have a Pois($\lambda$) distribution). Hence we define $Q^{(\lambda)}_{u,v}(t) = \max\{Z_i^{u,v}(t) : i \leq |W^\lambda_u|, j \leq |W^\lambda_v|\}$ (this is the indicator of the event that some $w \in W^\lambda_v$ met by time $t$ some $w' \in W^\lambda_u$) and set $\{u, v\} \in E_{t, \lambda}$ iff $Q^{(\lambda)}_{u,v}(t) = 1$.

**11 Proof of translation invariance and ergodicity**

Using the notation from Section 2.2, let $W_v := ((w_i^v(t))_{t \geq 0})_{i=1}^{\left|W^\lambda_v\right|}$ be the infinite walks that the walkers in $W_v$ performed.

**Lemma 11.1.** Let $G = (V, E)$ be an infinite connected graph. Let $\lambda > 0$, $\varepsilon > 0$ and $t \in \mathbb{Z}_+ \cup \{\infty\}$. Then for every $A \in \mathcal{F}_cylinder$, there exist a finite set $B = B(A, \varepsilon, t) \subset V$ and $A_\varepsilon$ such that the event $AC^{\lambda}_t(G) \in \text{graph}(A_\varepsilon)$ is in the $\sigma$-algebra generated by $(W_u : u \in B)$ and

$$P_\lambda[\text{AC}_t^{\lambda}(G) \in \text{graph}(A_\varepsilon \Delta A)] \leq \varepsilon.$$

This follows via elementary measure theoretical considerations, and so we omit the proof. **Proof of Proposition 2.5.** We first establish translation invariance. Let $\varphi \in \text{Aut}(G)$. We shall show that there exists a coupling of $AC^{\lambda}_t(G)$ and $\varphi(AC^{\lambda}_t(G))$ (i.e., a probability space in which both are realized) such that $AC^{\lambda}_t(G) = \varphi(AC^{\lambda}_t(G))$. This clearly implies the desired equality of the corresponding laws.

Note that if $(w(s))_{s \geq 0}$ has law $\mathbb{P}_v$ then $(\varphi(w(s)))_{s \geq 0}$ has law $\mathbb{P}_{\varphi(v)}$. Recall the construction of the SN model from §2.2 via $(M_v, ((w_n^v(s))_{s \in \mathbb{Z}_+})_{n \in \mathbb{N}})_{v \in V}$, where $(M_v)_{v \in V}$ are i.i.d. Pois($\lambda$) and $((w_n^v(s))_{s \in \mathbb{Z}_+})_{n \in \mathbb{N}}$ are independent LSRWs started from $v$ (i.e., having law $\mathbb{P}_v$). Denote this realization of $AC^{\lambda}_t(G)$ by $H := (V, E(H))$. Now consider a different realization obtained by replacing for all $v \in V$ the walks $((w_n^v(s))_{s \in \mathbb{Z}_+})_{n \in \mathbb{N}}$ by $((\varphi(w_n^{\varphi^{-1}(v)}(s)))_{s \in \mathbb{Z}_+})_{n \in \mathbb{N}}$ and replacing $M_v$ by $M_{\varphi^{-1}(v)}$. Denote it by $H' := (V, E(H'))$. Note that $\{u, v\} \in E(H') \text{ iff there is some } k \leq M_{\varphi^{-1}(u)}, m \leq M_{\varphi^{-1}(v)} \text{ and } s \leq t \text{ such that } w_k^{\varphi^{-1}(u)}(s) = w_m^{\varphi^{-1}(v)}(s)$. This occurs iff $\{\varphi^{-1}(u), \varphi^{-1}(v)\} \in E(H)$, or equivalently iff $\{u, v\}$ is an edge in $\varphi(H)$. That is $H' = \varphi(H)$.

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We now prove ergodicity. Let $\mathcal{A} \in \mathcal{I}$. Fix some $t \in \mathbb{Z}_+ \cup \{\infty\}$. We seek to show that $P_\lambda[AC^\lambda_t \in \text{graph}(\mathcal{A})] \in \{0, 1\}$. Let $\varepsilon > 0$. By Lemma 11.1, there exist a finite set $B_\varepsilon \subseteq \mathcal{V}$ and an event $\mathcal{A}_\varepsilon$ such that $\{AC^\lambda_t(G) \in \text{graph}(\mathcal{A}_\varepsilon)\}$ is in the $\sigma$-algebra generated by $(W_b(t))_{b \in B_\varepsilon}$ and $P_\lambda[AC^\lambda_t(G) \in \text{graph}(\mathcal{A}_\varepsilon \triangle \mathcal{A})] \leq \varepsilon$. Let $r_\varepsilon := \max\{\text{dist}(u, v) : u, v \in B_\varepsilon\}$. Let $\varphi_\varepsilon \in \text{Aut}(\mathcal{G})$ be such that $\text{dist}(v, \varphi_\varepsilon(v)) > 2r_\varepsilon$ for all $v \in \mathcal{V}$.

The event $\{AC^\lambda_t(G) \in \text{graph}(\varphi_\varepsilon(\mathcal{A}_\varepsilon))\}$ is in the $\sigma$-algebra generated by $(W_{\varphi_\varepsilon(b)}(t))_{b \in B_\varepsilon}$. By our choice of $\varphi_\varepsilon$, the sets $B_\varepsilon$ and $\{\varphi_\varepsilon(b) : b \in B_\varepsilon\}$ are disjoint. Hence the events $\{AC^\lambda_t(G) \in \text{graph}(\varphi_\varepsilon(\mathcal{A}_\varepsilon))\}$ and $\{AC^\lambda_t(G) \in \text{graph}(\mathcal{A}_\varepsilon)\}$ are independent, as they depend on disjoint sets of walkers. By translation invariance and the fact that $\mathcal{A} \in \mathcal{I}$ (and so $\varphi_\varepsilon(\mathcal{A}_\varepsilon) \triangle \mathcal{A} = \varphi_\varepsilon(\mathcal{A}_\varepsilon \triangle \mathcal{A})$)

$$P_\lambda[AC^\lambda_t(G) \in \text{graph}(\varphi_\varepsilon(\mathcal{A}_\varepsilon) \triangle \mathcal{A})] = P_\lambda[AC^\lambda_t(G) \in \text{graph}(\mathcal{A}_\varepsilon \triangle \mathcal{A})] \leq \varepsilon.$$ 

Hence $P_\lambda[AC^\lambda_t(G) \in \text{graph}(\mathcal{A}_\varepsilon \cap \varphi_\varepsilon(\mathcal{A}_\varepsilon) \triangle \mathcal{A})] \leq 2\varepsilon$ and thus

$$P_\lambda[AC^\lambda_t(G) \in \text{graph}(\mathcal{A})] = \lim_{\varepsilon \to 0} P_\lambda[AC^\lambda_t(G) \in \text{graph}(\mathcal{A}_\varepsilon \cap \varphi_\varepsilon(\mathcal{A}_\varepsilon))]$$

$$= \lim_{\varepsilon \to 0} P_\lambda[AC^\lambda_t(G) \in \text{graph}(\mathcal{A}_\varepsilon)]P_\lambda[AC^\lambda_t(G) \in \text{graph}(\varphi_\varepsilon(\mathcal{A}_\varepsilon))]$$

$$= \lim_{\varepsilon \to 0} P_\lambda[AC^\lambda_t(G) \in \text{graph}(\mathcal{A}_\varepsilon)]^2 = P_\lambda[AC^\lambda_t(G) \in \text{graph}(\mathcal{A})]^2.$$ 

Thus indeed $P_\lambda[AC^\lambda_t(G) \in \text{graph}(\mathcal{A})] \in \{0, 1\}$, as desired. \[\square\]

12 Proof of Proposition 8.2

We denote the walk performed by a walker $w$ by $(w(t))_{t \geq 0}$. Recall that $\mathcal{W}_w(t)$ is the set of walkers whose location at time $t$ is $v$ and that for $B \subseteq \mathcal{V}$ and $t \geq 0$, $\mathcal{W}_B(t) := \cup_{b \in B} \mathcal{W}_b(t)$ is the set of walkers occupying $B$ at time $t$. We denote the lexicographic order by $\prec$. Our use of the lexicographic order below is just a mean of preforming the bookkeeping in a manner which avoids double-counting (so that each walker is recruited to the exploration process at most once). It plays no additional role in the argument.

Proof of Proposition 5.2: At stage zero, we start the exploration process of $\text{FC}(o)$ by setting $\mathcal{W}_{0,0} := \mathcal{W}_o$ and $\mathcal{A}_{0,0} = \{v\}$. We label the walkers in $\mathcal{W}_{0,0}$ as $w_{0,0,1}, \ldots, w_{0,0,|\mathcal{W}_{0,0}|}$.

If $\mathcal{W}_o$ is empty the exploration process is completed. Otherwise, at stage one we set

$$\mathcal{A}_{1,1} := \{w(1) : w \in \mathcal{W}_{0,0}\} \quad \text{and} \quad \mathcal{W}_{1,1} := \{w \in \mathcal{W}_{\mathcal{A}_{1,1}}(1) : w \notin \mathcal{W}_{0,0}\}$$

to be the collection of walkers not belonging to $\mathcal{W}_{0,0}$, which have the same position at time 1 as some walker in $\mathcal{W}_{0,0}$. We say that $w \in \mathcal{W}_{1,1}$ is an offspring of $w_{0,0,j}$ if $w(1) = w_{0,0,j}(1)$ and $j$ is the minimal integer such that this holds. Finally, we label the elements of $\mathcal{W}_{1,1}$ as $w_{1,1,1}, \ldots, w_{1,1,|\mathcal{W}_{1,1}|}$.
The first “interesting” stage of the process is stage 2, thus we describe it before proceeding to the description of a general stage. Let

$$A_{2,0} := \{w(0) : w \in W_{1,1}\} \quad \text{and} \quad A_{2,2} := \{w(2) : w \in W_{0,0} \cup W_{1,1}\}. $$

We set

$$W_{2,0} := \{w \in W_{A_{2,0}}(0) : w \notin W_{1,1}\} \quad \text{and} \quad W_{2,2} := \{w \in W_{A_{2,2}}(2) : w \notin \cup_{(i,j) < (2,2)} W_{i,j}\}. $$

In words, $W_{i,j}$ is the set of walkers recruited to the process at stage $i$ of the exploration process, by meeting at time $j$ some walker which was recruited to the exploration process at an earlier stage (not necessarily an earlier time). These are the walkers which at time $j$ visit the set $A_{i,j}$ but for all $(i', j') < (i, j)$ avoided $A_{i',j'}$ at time $j'$. Once a walker is recruited to the exploration process by joining $W_{i,j}$ at stage $i$, we then expose at each stage $i + \ell$ (where $\ell \in \mathbb{N}$) its location at time $j + \ell$ and if $\ell \leq j$ we also expose its position at time $j - \ell$.

In particular, for every $t$, for some values of $s$ (namely, for $s \leq t$ such that $t - s$ is even) we expose at the $t$-th stage of the exploration process the location at time $s$ of some particles which have been recruited to the exploration process prior to stage $t$ (namely of the ones in $W_{i,j}$ for $(i, j)$ such that either $j + (t - i) = s$ or $j - (t - i) = s$). We denote the collection of these locations by

$$A_{t,s} := \cup_{(i,j) : j + (t - i) = s \text{ or } j - (t - i) = s} \{w(s) : w \in W_{i,j}\}. $$

Finally, we let $W_{t,s}$ be the collection of walkers in $W_{A_{t,s}}(s)$ (i.e., the ones occupying $A_{t,s}$ at time $s$) which do not belong to $W_{r,s'}$ for any $(t', s') < (t, s)$.

The parent of $w \in W_{2,0}$ (respectively, $W_{2,2}$) is defined to be $w_{1,1,k} \in W_{1,1}$ (respectively, $w_{i,j,k} \in W_{0,0} \cup W_{1,1}$) such that $w(0) = w_{1,1,k}(0)$ (respectively, $w(2) = w_{i,j,k}(2)$) and $(1, 1, k)$ (respectively, $(i, j, k)$) is minimal w.r.t. $\prec$. Finally, for $(i, j) \in \{(2, 0), (2, 2)\}$ we label the walkers in $W_{i,j}$ as $w_{i,j,1}, \ldots, w_{i,j,|W_{i,j}|}$.

The sets $A_{r,s}$ and $W_{r,s} = \{w_{r,s,1}, \ldots, w_{r,s,|W_{r,s}|}\}$ (where $0 \leq s \leq r$ is of the same parity as $r$) are defined inductively so that the following holds:

1. $A_{r,s} := \{w(s) : w \in \cup_{(i,j) \in F_{r,s} \cup B_{r,s}} W_{i,j}\}$, where

$$F_{r,s} := \{(i,j) : (i,j) \prec (r,s) \text{ and } r-i = s-j > 0\} \quad \text{and} \quad B_{r,s} := \{(i,j) : j-s = r-i > 0\}. $$

(in simple words, as described above, $A_{r,s}$ are the positions explored by the exploration process at stage $r$ corresponding to time $s$ of some walkers. This walkers were recruited at an earlier stage, either at an earlier time or at a latter time. If they were recruited at stage $i$ and time $j$ then by construction in the first case $(i,j) \in F_{r,s}$, while in the second case $(i,j) \in B_{r,s}$.)
(2) \(W_{r,s} := \{w \in W_{A_{r,s}}(s) : w \notin \cup_{(i,j) \prec (r,s)} W_{i,j}\}\). Note that this is the set of walkers which joined the exploration process at stage \(r\) and time \(s\).

It follows that

\[
\cup_{(r,s) : r \geq s, r-s \text{ is even}} W_{r,s} = FC(o).
\]

We now describe the assignment of offspring to walkers. In the \(r\)-th stage we expose the sets \(A_{r,s}\) (where \(0 \leq s \leq r\) is of the same parity as \(r\)) sequentially according to the order \(\prec\). We expose each \(A_{r,s}\) by exposing sequentially the positions of the walkers in \(\cup_{(i,j) \in F_{r,s} \cup B_{r,s}} W_{i,j}\) one walker at a time, according to the order \(\prec\) (over the indices of the walkers \((i, j, k)\) such that \((i, j) \in F_{r,s} \cup B_{r,s}\) and \(1 \leq k \leq |W_{i,j}|\)). We say that \(w \in W_{r,s}\) is an offspring of \(w_{i,j,k}\) (where \((i, j) \in F_{r,s} \cup B_{r,s}\) and \(1 \leq k \leq |W_{i,j}|\)) if \(w(s) = w_{i,j,k}(s)\) but for all \((i', j', k') \prec (i, j, k)\) such that \((i', j') \in F_{r,s} \cup B_{r,s}\) and \(1 \leq k' \leq |W_{i',j'}|\) we have that \(w(s) \neq w'_{i',j',k'}(s)\). Moreover, as \(w \notin \cup_{(r',j') \prec (r,s)} W_{r',j'}\) (by the definition of \(W_{r,s}\) and the assumption that \(w \in W_{r,s}\)), we also have that \(w(\ell) \notin A_{n,\ell}\) for all \(0 \leq \ell \leq n \leq r\) (where \(n - \ell\) is even) such that \((n, \ell) \prec (r, s)\). If \(s > j\) (respectively, \(j > s\)) we say that \(w\) is a forward (respectively, backward) offspring of \(w_{i,j,k}\). Let \(B_{i,j,k}(r-i)\) and \(F_{i,j,k}(r-i)\) be the backward and forward (resp.) offspring of \(w_{i,j,k}\) at stage \(r\). Denote by \(B_{i,j,k}(r-i)\) and \(F_{i,j,k}(r-i)\) the collection of space-time coordinates which (as described above) a walker in \(B_{i,j,k}(r-i)\) and \(F_{i,j,k}(r-i)\) (respectively) has to avoid, in order to have not been recruited to the exploration process prior to the exposure of \(B_{i,j,k}(r-i)\) or \(F_{i,j,k}(r-i)\), respectively (namely, these are the space-time coordinates exposed prior to the exposure of \(B_{i,j,k}(r-i)\) and \(F_{i,j,k}(r-i)\), respectively).

We think of a walker \(w_{i,j,k}\) as performing a forward walk, \(fw_{i,j,k}(\ell) := w(j + \ell)\) and a backward walk (of length \(j\)) \(bw_{i,j,k}(\ell) = w(j - \ell)\). At each stage \(r \geq i\) we expose one additional step of \(fw_{i,j,k}\) (namely, \(fw_{i,j,k}(r-i) = w(j + (r-i))\)) and if \(j \geq r - i\) also one additional step of \(bw_{i,j,k}\) (namely, \(bw_{i,j,k}(r-i) = w(j - (r-i))\)). Note that the forward (respectively, backward) offspring of \(w_{i,j,k}\) at stage \(r\) are precisely the collection of all walkers \(w\) whose location at time \(j + r - i\) (respectively, \(j - r + i\)) is \(w_{i,j,k}(j + r - i)\) (respectively, \(w_{i,j,k}(j - r + i)\)) so that \((w(\ell), \ell) \notin F_{i,j,k}(r-i)\) (respectively, \(w(\ell) \notin B_{i,j,k}(r-i)\)) for all \(0 \leq \ell \leq r\).

Recall that \(\Gamma_r\) is the collection of all walks of length \(r\) in \(G\) and that for \(\gamma \in \Gamma_r\), we denote the number of walkers which performed the walk \(\gamma\) by \(X_\gamma \sim \text{Pois}(\lambda p(\gamma))\), where \(p(\gamma) := \prod_{i=0}^{r-1} P(\gamma_i, \gamma_{i+1})\).

Let \(\Gamma_{i,j,k,r,\ell}\) (respectively, \(\Gamma_{i,j,k,r,b}\)) be the collection of all \(\gamma = (\gamma_0, \ldots, \gamma_r) \in \Gamma_r\) such that \((\gamma_\ell, \ell) \notin F_{i,j,k}(r-i)\) for all \(\ell\) and \(\gamma_{j+r-i} = w_{i,j,k}(j + r - i)\) (respectively, \((\gamma_\ell, \ell) \notin B_{i,j,k}(r-i)\) for all \(\ell\) and \(\gamma_{j-r+i} = w_{i,j,k}(j - r + i)\)). By Poisson thinning, given \(F_{i,j,k}(r-i)\) and \(w_{i,j,k}(j+r-i)\) (respectively, \(B_{i,j,k}(r-i)\) and \(w_{i,j,k}(j-r+i)\)), \((X_\gamma)_{\gamma \in \Gamma_{i,j,k,r,\ell}}\) (respectively, \((X_\gamma)_{\gamma \in \Gamma_{i,j,k,r,b}}\)) are independent Poisson r.v.’s with mean \(\lambda p(\gamma)\), respectively.

Now, consider the case that after exposing \(w_{i,j,k}(j + r - i)\) (respectively, \(w_{i,j,k}(j - r + i)\)), for each

\[
\gamma \in \{\gamma' \in \Gamma_r : \gamma'_{j+r-i} = w_{i,j,k}(j + r - i)\} \setminus \Gamma_{i,j,k,r,\ell}
\]
(respectively, \( \gamma \in \{ \gamma' \in \Gamma_r : \gamma'_{j-r+i} = w_{i,j,k}(j-r+i) \} \setminus \Gamma_{i,j,k,r,b} \))

we “plant” \( \lambda p(\gamma) \) new “dummy particles” (independently for different such \( \gamma \)'s) which perform the path \( \gamma \), and then continue their walk after time \( r \) randomly. The dummy particles do not discover new walkers in the following stages of the exploration process (i.e., they do not have any offspring and the trajectory of their walk plays no role in the following stages). If we count the dummy particles as part of the offspring of \( w_{i,j,k} \) corresponding to its forward step at stage \( r \), then we have that \((X_{\gamma}^i,j,k,r,f)_{\gamma \in \Gamma_r : \gamma_{j-r+i} = w_{i,j,k}(j-r+i)} \) are independent Poisson r.v.'s and \( \mathbb{E}_\lambda[X_{\gamma}^i,j,k,r,f] = \lambda p(\gamma) \) for all \( \gamma \in \{ \gamma' \in \Gamma_r : \gamma'_{j-r+i} = w_{i,j,k}(j-r+i) \} \), where \( X_{\gamma}^i,j,k,r,f \) is the number of offspring of \( w_{i,j,k} \) corresponding to its forward step at stage \( r \) who perform the walk \( \gamma \). By Poisson thinning, this is the same as having Pois(\( \lambda \)) offspring, each performing an independent \( \mathbb{Z}_+ \)-indexed LSRW on \( G \), conditioned to be at \( w_{i,j,k}(j+r-i) \) at time \( j+r-i \). A similar statement holds for the number of offspring of \( w_{i,j,k} \) corresponding to its backwards step at stage \( r \).

Recall the construction of the sets \( V_{r,s} = \{ v_{r,s,1}, \ldots, v_{r,s,|V_{r,s}|} \} \) from the equivalent representation of LBRW(\( \mu, o \)). It is not hard to prove that the sets \( W_{r,s} \) and \( V_{r,s} \) can be coupled (for all \( 0 \leq s \leq r \) so that \( r-s \) is even) so that \( W_{r,s} \subseteq V_{r,s} \). More precisely, this can be done so that for all \( k \leq |W_{r,s}| \) we have that \( v_{r,s,k}(t) = w_{r,s,k}(t) \) for all \( t \geq 0 \). We leave the details to the reader. \( \square \)