In between random walk and rotor walk

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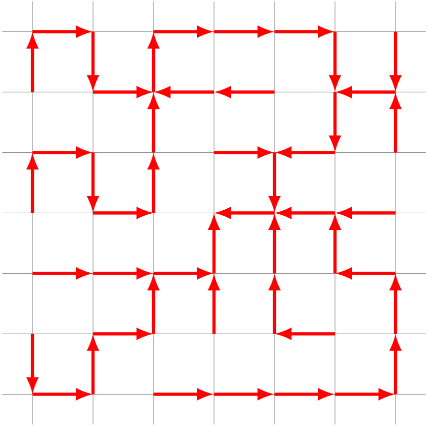
Joint with Lila Greco, Lionel Levine, Peter Li



Motivation: Exploring Taipei

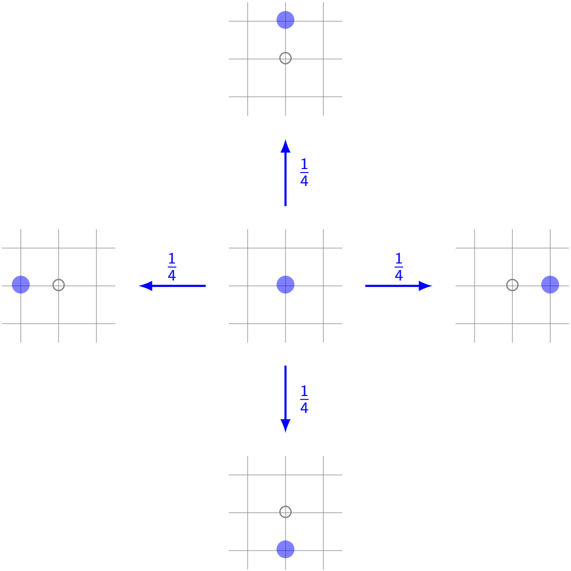
Random model vs deterministic model

Random walk

Rotor walk

Simple random walk on $\mathbb{Z}^2$

Simple random walk on $\mathbb{Z}^2$



Simple random walk on $\mathbb{Z}^2$

- Visits every site infinitely often? Yes!
- Number of distinct points visited in n steps is $\asymp \frac{n}{\log n}$.
- Scaling limit? The standard 2-D Brownian motion:

$$\left(\frac{1}{\sqrt{n}} X([nt])\right)_{t \geq 0} \overset{n \to \infty}{\Longrightarrow} \frac{1}{\sqrt{2}} (B_1(t), B_2(t))_{t \geq 0},$$

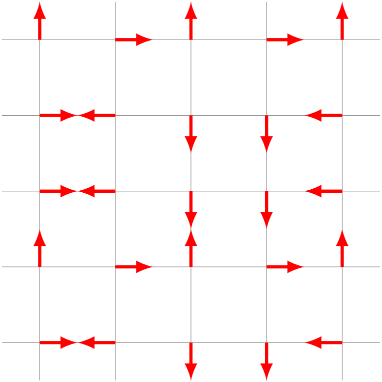
where

$$X(t) := \text{ Location of the walker at time-step } t,$$
$$B_1, B_2 := \text{Independent standard Brownian motions.}$$

Rotor walk on $\mathbb{Z}^2$

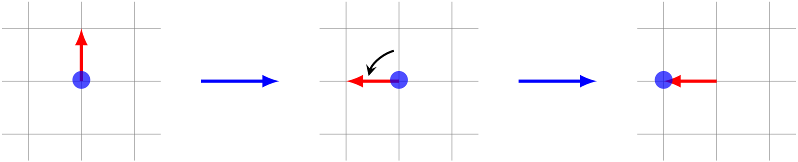
Rotor walk on $\mathbb{Z}^2$

Put a signpost (rotor) at every vertex.



Rotor walk on $\mathbb{Z}^2$

Turn the signpost at your location 90° counterclockwise, then follow its new direction.



The signpost says:
"This is the way you went the last time you were here",
(assuming you ever were!)

Rotor walk on $\mathbb{Z}^2$

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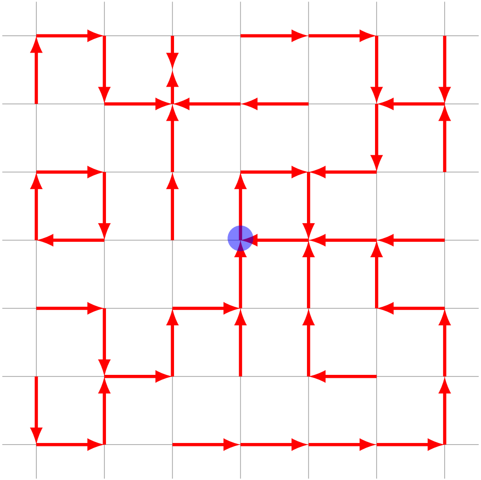

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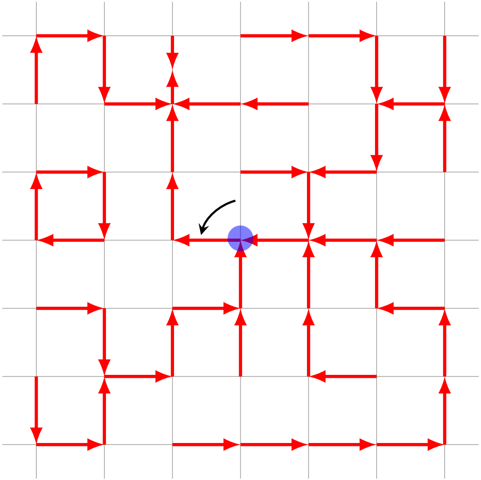

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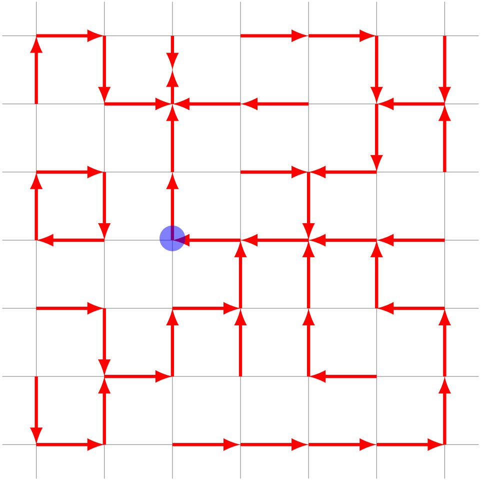

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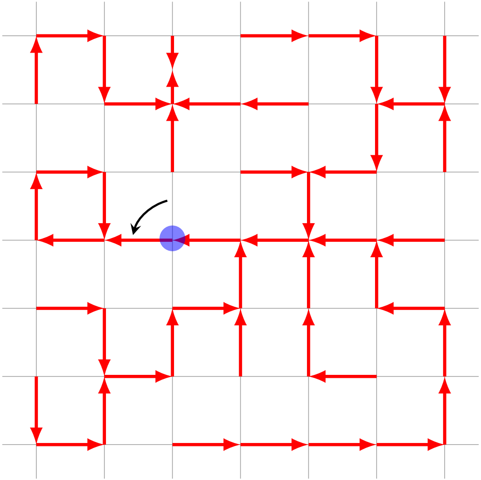

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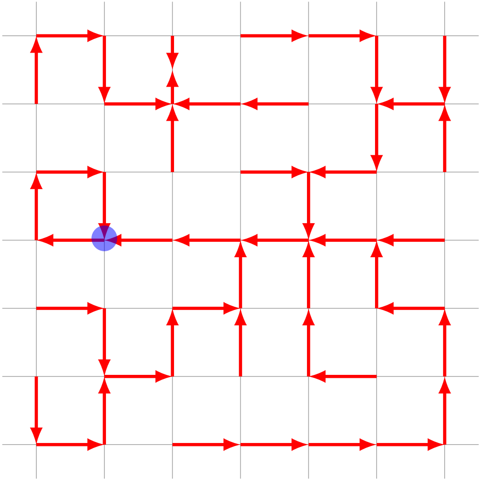

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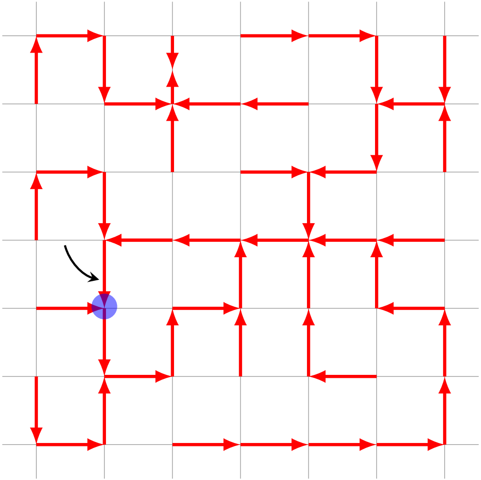

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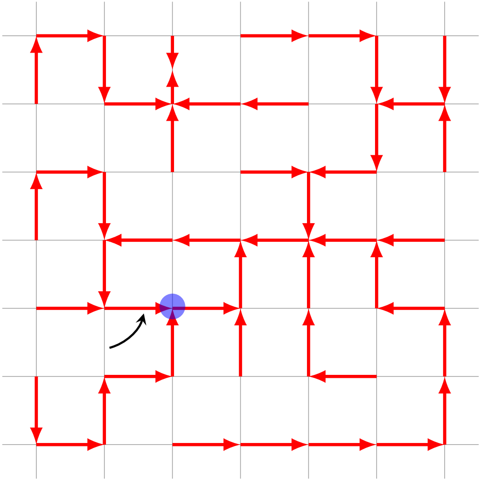

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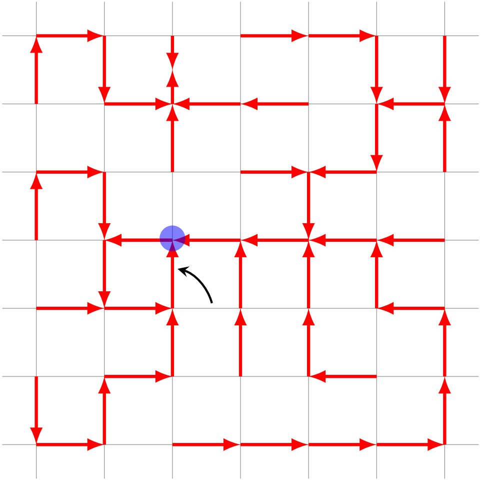

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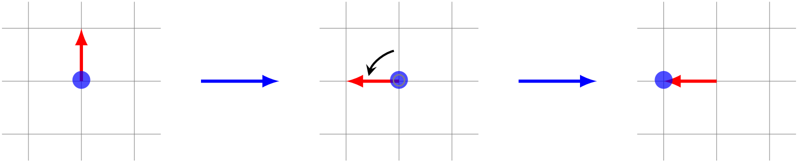


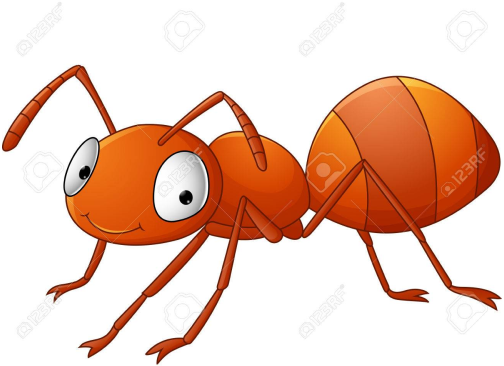
The signpost says:
“This is the way you went the last time you were here“,
(assuming you ever were!)

Why rotor walk?

Randomness can be (was) expensive to simulate!

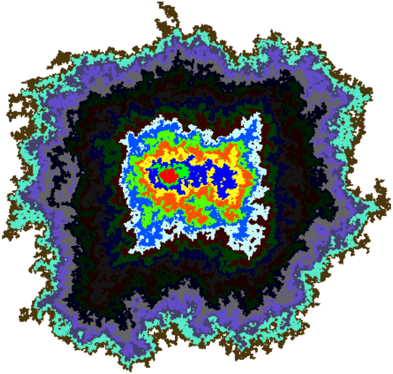
Why rotor walk?

As a model for ants' foraging strategy.



Why rotor walk?

As a model of self-organized criticality for statistical mechanics.



Visited sites after 80 returns to the origin (by Laura Florescu).

Conjectures for rotor walk on $\mathbb{Z}^2$

For initial signposts i.i.d. uniform among the four directions,

- (PDDK '96) Visits every site infinitely often?
- (PDDK '96) No. of points visited in n steps is $\asymp n^{2/3}$?

  (compare with $n/\log n$ for the simple random walk.)
- (Kapri-Dhar '09) Asymptotic shape of $\{X(1), \ldots, X(n)\}$ is a disc?

More randomness please!

Well studied

Many open problems

Random

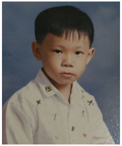
Deterministic

More randomness please!

Well studied

Random

Let's study this!!!

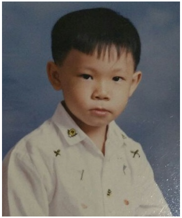


Something in between

Many open problems

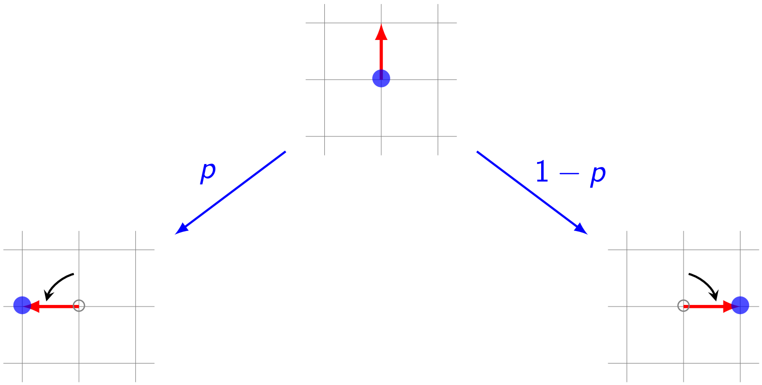
Deterministic

p-rotor walk on $\mathbb{Z}^2$



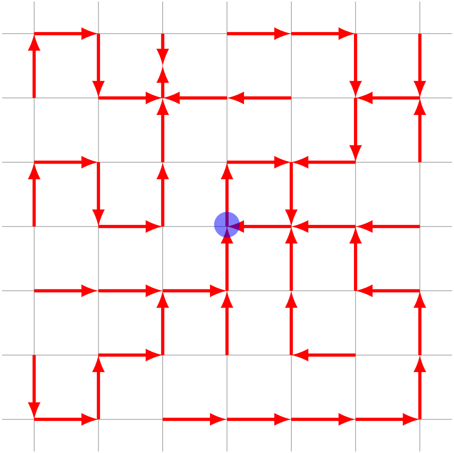
p-rotor walk on $\mathbb{Z}^2$

With probability p, turn the signpost 90° counter-clockwise.
With probability $1-p$, turn the signpost 90° clockwise.



p-rotor walk on $\mathbb{Z}^2$

Follow rotor walk rule with probability p,
do the opposite with probability $1 - p$.



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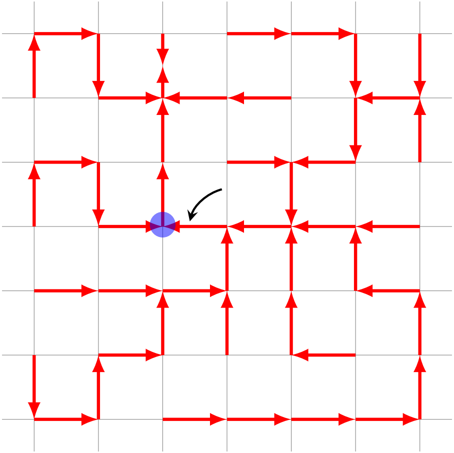

Follow the rule.

p-rotor walk on $\mathbb{Z}^2$

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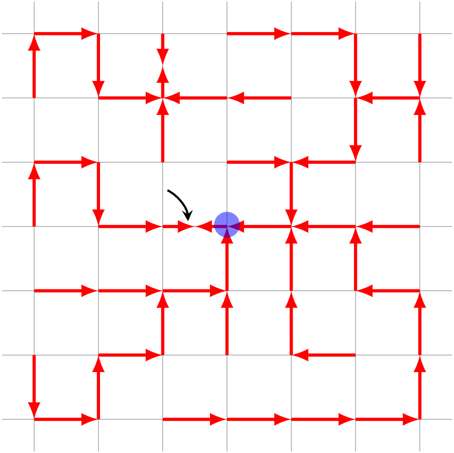

Do the opposite.

p-rotor walk on $\mathbb{Z}^2$

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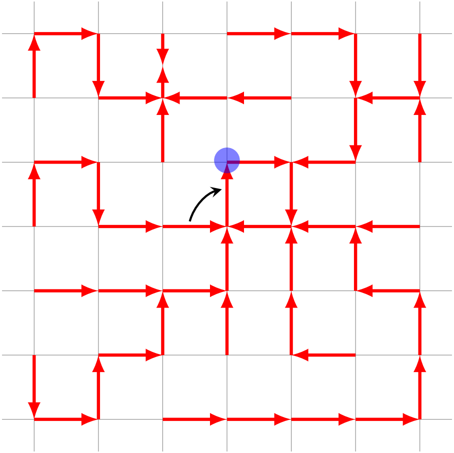
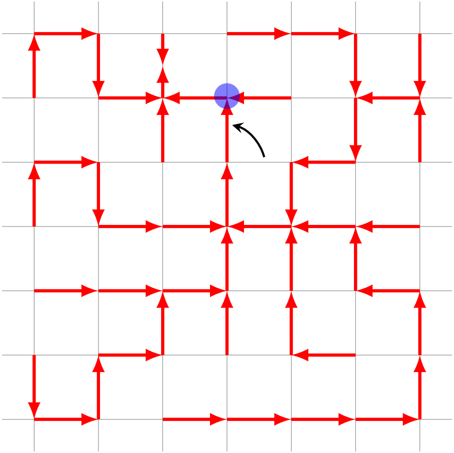


Do the opposite again.

p-rotor walk on $\mathbb{Z}^2$

Follow rotor walk rule with probability p,
do the opposite with probability $1 - p$.



Follow the rule.

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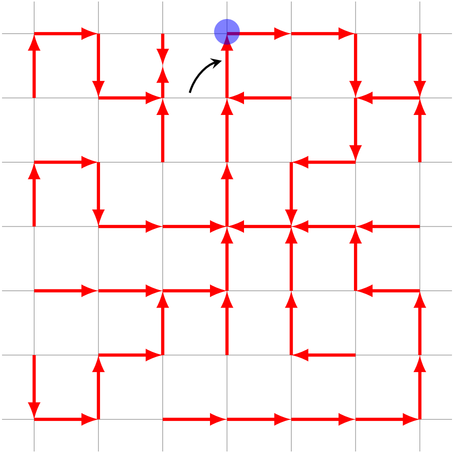

Do the opposite.

p-rotor walk on $\mathbb{Z}^2$

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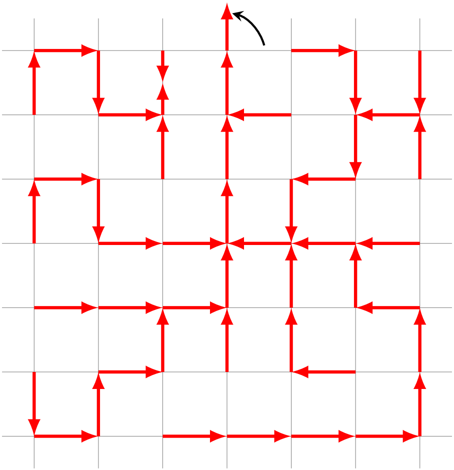

Ops...

p-rotor walk on $\mathbb{Z}^2$

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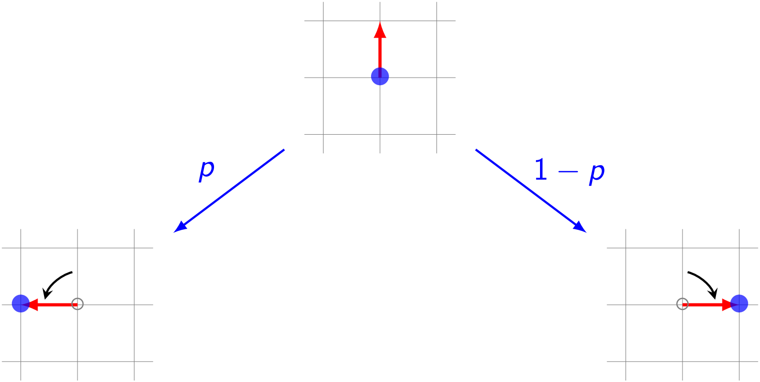


This model becomes the rotor walk when $p = 1$,
but it is never a simple random walk.

Recurrence result for p-rotor walk

Recurrence for p-rotor walk on $\mathbb{Z}^2$

Theorem (C., '23)

Let $p = \frac{1}{2}$ and let the i.i.d uniform among four directions be the initial signpost configuration. Then the p-rotor walk visits every vertex infinitely often almost surely.

Contrast this with rotor walk, where recurrence is still an open problem (PDDK '96).

Proof of recurrence for the simple random walk

Consider the following martingale:

$$M(t) := a(X(t)) \; - \; N(t),$$

where

$$\begin{aligned} X(t) \;&:=\; \text{Location of walker at time } t; \\ a(x) \;&:=\; \text{Potential kernel of } x \text{ at } \mathbb{Z}^2; \\ N(t) \;&:=\; \text{Number of times walker leaving } o \text{ by time } t. \end{aligned}$$

Proof of recurrence for the simple random walk

Use the optional stopping theorem:

$$0 = \mathbb{E}[M(\tau(r))] \;\approx\; \frac{2}{\pi}\ln r\,(1 - p_{\mathrm{ret}}(r)) - 1,$$

where

$$\begin{aligned} \partial B_r \;&:=\; \text{Boundary of ball of radius } r; \\ \tau(r) \;&:=\; \text{First time walker reaching } \partial B_r \text{ or returning to } o; \\ p_{\mathrm{ret}}(r) \;&:=\; \text{Probability of reaching } \partial B_r \text{ before returning to } o. \end{aligned}$$

Proof of recurrence for the simple random walk

We rewrite the equation to

$$p_{\text{ret}}(r) \;\approx\; 1 - \frac{\pi}{2\ln r}.$$

Taking the limit $r \to \infty$, we conclude

$$p_{\text{rec}} \;=\; 1 - \lim_{r\to\infty} \frac{\pi}{2\ln r} = 1,$$

where

$$p_{\text{rec}} \;=\; \text{Probability of walker returning to } o,$$

is the recurrence probability.

Proof of recurrence for p-rotor walk

Consider the following martingale:

$$M(t) := a(X(t)) - N(t) + \underbrace{\sum_{x \in \{X_0, \dots, X_t\}} \mathtt{w}(x; \rho_t)}_{\text{compensator}}.$$

By the same argument as before,

$$p_{\text{rec}} = 1 - \lim_{r \to \infty} \frac{\pi}{2 \ln r} \left(\sum_{|x| \leq r} \mathbb{E}[\mathtt{w}(x; \rho_{\tau(r)})] \right).$$

Proof of recurrence for p-rotor walk

We can estimate the terms in the compensator locally by

$$\left|\mathbb{E}[\mathtt{w}(x;\rho_{\tau(r)})]\right| \;\leq\; \left(1-\frac{1}{2^{70}}\right)\frac{2}{\pi|x|^2}.$$

Plugging this estimate into previous equation,

$$p_{\mathrm{rec}} \geq 1 - \lim_{r\to\infty}\frac{\pi}{2\ln r}\left(\sum_{|x|\leq r}\left(1-\frac{1}{2^{70}}\right)\frac{2}{\pi|x|^2}\right) \;=\; \frac{1}{2^{70}} > 0.$$

By Kolmogorov zero-one law, the recurrence probability is 1.

So we have proved ...

Theorem (C., '23)

Let $p = \frac{1}{2}$ and let the i.i.d uniform among four directions be the initial signpost configuration. Then the p-rotor walk visits every vertex infinitely often almost surely.

We need to assume $p = \frac{1}{2}$, as otherwise the bound for the compensator decays linearly instead of quadratically.

Open problem

Conjecture

Let $p \neq \frac{1}{2}$. Prove that p-rotor walk with i.i.d. uniform signpost configuration is recurrent.

Obstacle: Need to find a better estimate of the compensator:

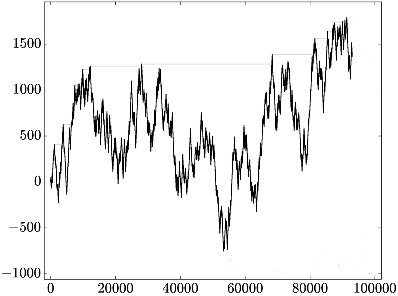
$$\underbrace{M(t)}_{\text{martingale}} := a(X(t)) \; - \; N(t) \; + \underbrace{\sum_{x \in \{X_0, \ldots, X_t\}} \mathtt{w}(x; \rho_t)}_{\text{compensator}}.$$

Scaling limit result for p-rotor walk

Scaling limit for p-rotor walk on $\mathbb{Z}$

(Huss, Levine, Sava-Huss 18) The scaling limit for p-rotor walk on $\mathbb{Z}$ is a perturbed Brownian motion $(Y(t))_{t\geq 0}$,

$$Y(t) = \underbrace{B(t)}_{\substack{\text{standard}\\ \text{Brownian}\\ \text{motion}}} + \underbrace{a \sup_{0\leq s\leq t} Y(s)}_{\substack{\text{perturbation at}\\ \text{maximum}}} + \underbrace{b \inf_{0\leq s\leq t} Y(s)}_{\substack{\text{perturbation at}\\ \text{minimum}}}, \qquad t \geq 0.$$



$Y(t)$ for $a = -0.998$, and $b = 0$ (by Wilfried Huss).

Scaling limit for p-rotor walk on $\mathbb{Z}^2$

Question: Is the scaling limit for p-rotor walk on $\mathbb{Z}^2$ a "2-D perturbed Brownian motion"?

Problem: How to define "2-D perturbed Brownian motion"?.

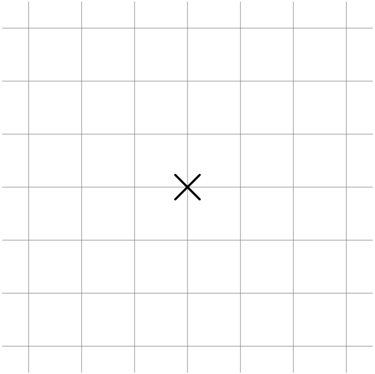
Scaling limit for p-rotor walk on $\mathbb{Z}^2$

Question: Is the scaling limit for p-rotor walk on $\mathbb{Z}^2$ a "2-D perturbed Brownian motion"?

Problem: How to define "2-D perturbed Brownian motion"?.

Conjecture: The scaling limit for p-rotor walk on $\mathbb{Z}^2$ when $p = \frac{1}{2}$ is the standard 2-D Brownian motion.

Uniform spanning forest plus one edge (USF$^+$)



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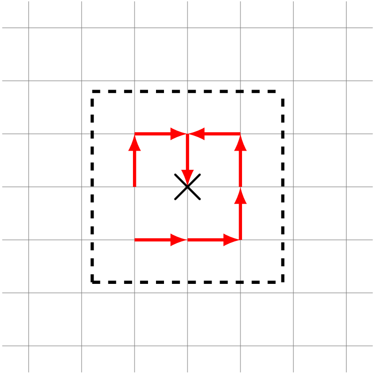
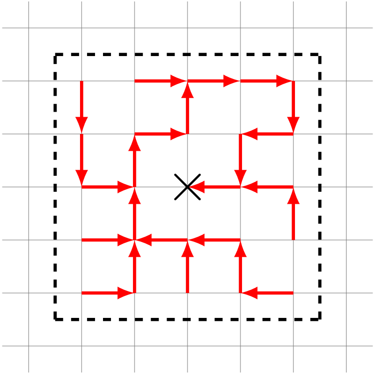


Pick a spanning tree of the black box directed to the origin (uniformly at random).

Uniform spanning forest plus one edge (USF$^+$)



Take the limit as the black box grows until it covers $\mathbb{Z}^2$.

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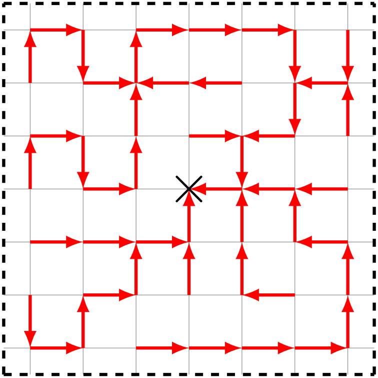

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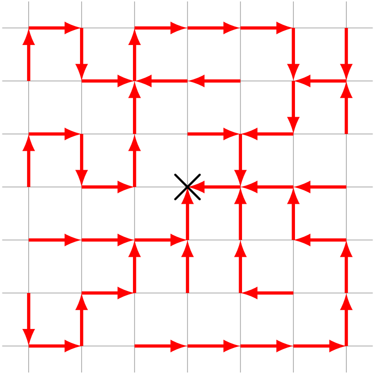

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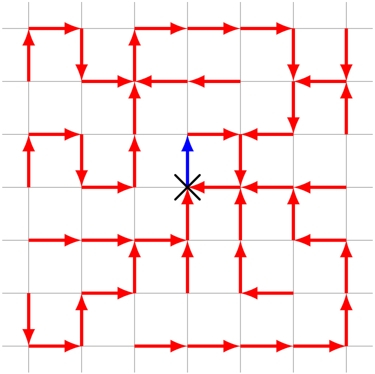


Add a signpost to the origin, uniform among the four directions.

Scaling limit for p-rotor walk on $\mathbb{Z}^2$

Theorem (C., Greco, Levine, Li '21)

Let $p = \frac{1}{2}$ and let the uniform spanning forest plus one edge be the initial signpost configuration. Then, with probability 1, the p-rotor walk on $\mathbb{Z}^2$ scales to the standard 2-D Brownian motion:

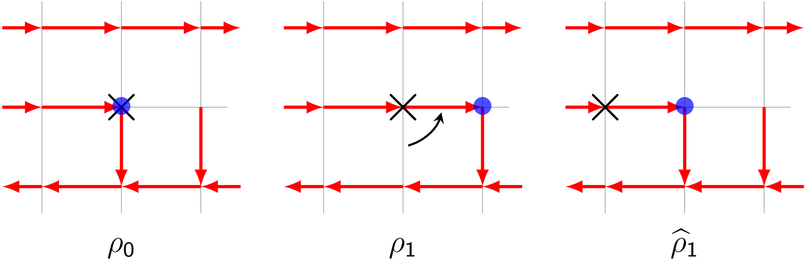
$$\frac{1}{\sqrt{n}}(\underbrace{X_{[nt]}}_{\substack{\text{location of the} \\ \text{walker at time } [nt]}})_{t\geq 0} \overset{n\to\infty}{\Longrightarrow} \frac{1}{\sqrt{2}}(\underbrace{B_1(t), B_2(t)}_{\substack{\text{independent} \\ \text{Brownian motions}}})_{t\geq 0}.$$

Disclaimer: Proof in the paper was for h-v walks, not p-rotor walks.

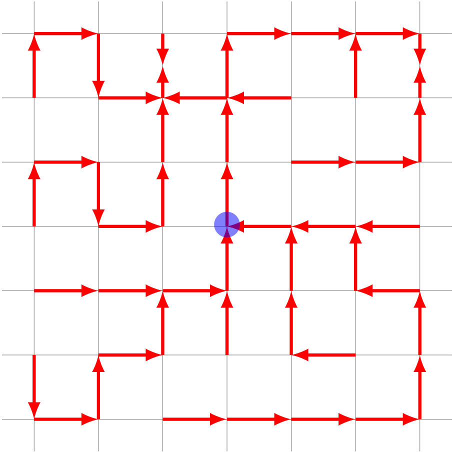
Stationarity from the walker's POV

A signpost configuration $(\rho_0(x))_{x\in\mathbb{Z}^2}$ is stationary in time from the walker's point of view if

$$\underbrace{(\widehat{\rho}_1(x))_{x\in\mathbb{Z}^2}}_{\substack{\text{signpost conf. at}\\ \text{time 1 from walker's POV}}} := (\rho_1(x - X_1))_{x\in\mathbb{Z}^2} \overset{d}{=} \underbrace{(\rho_0(x))_{x\in\mathbb{Z}^2}}_{\substack{\text{signpost conf.}\\ \text{at time 0}}}.$$



Why is USF^+ stationary from walker's POV?



The signposts at previously visited vertices
form a tree oriented toward the walker.

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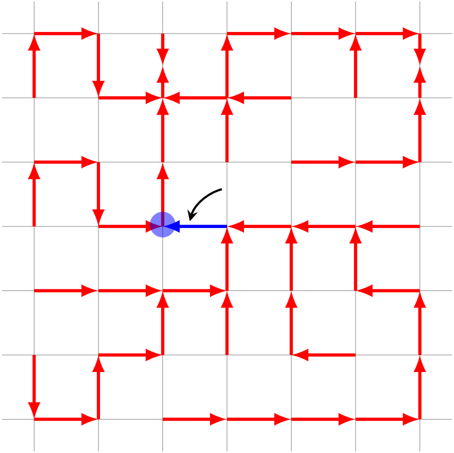

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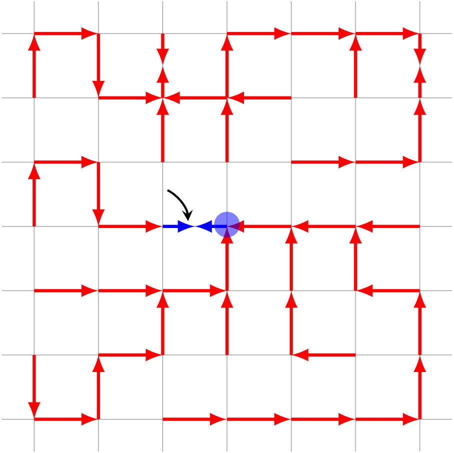
Why is USF$^+$ stationary from walker's POV?



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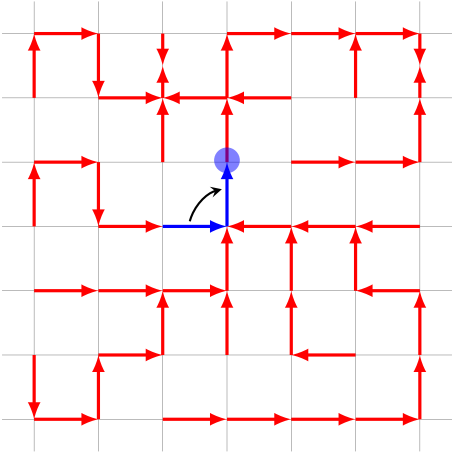

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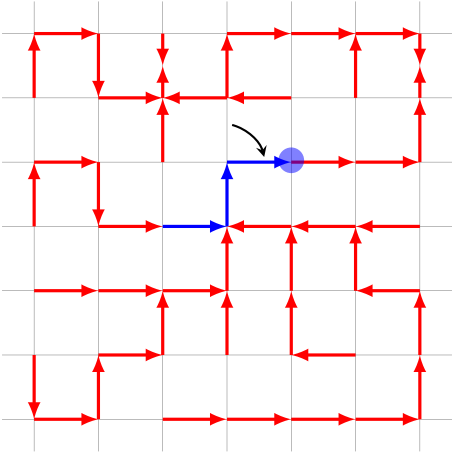

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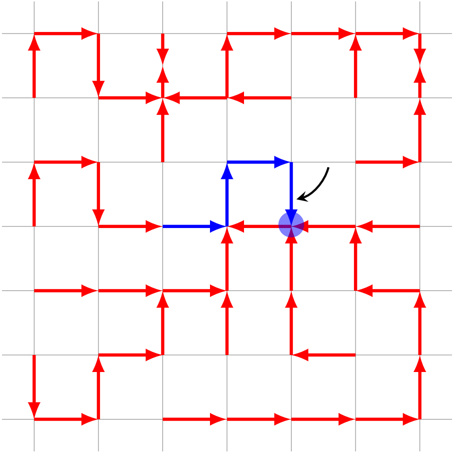

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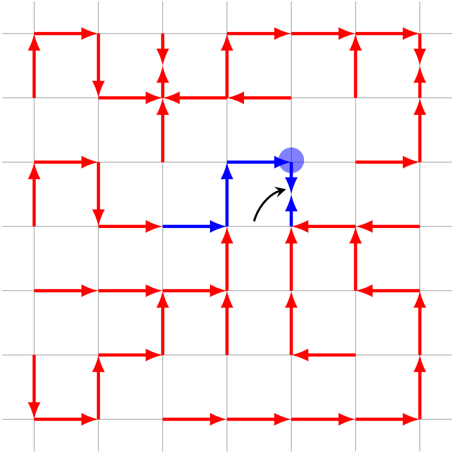

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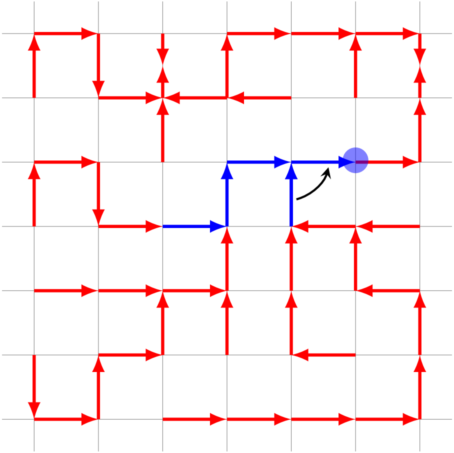

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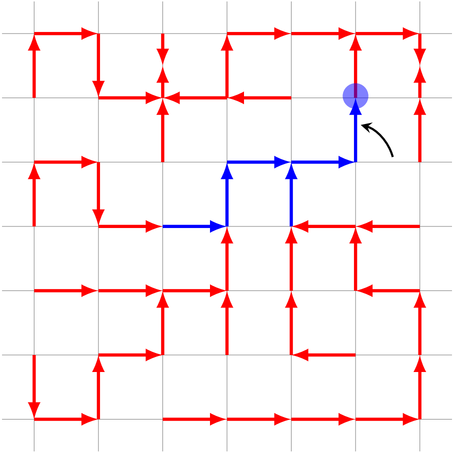
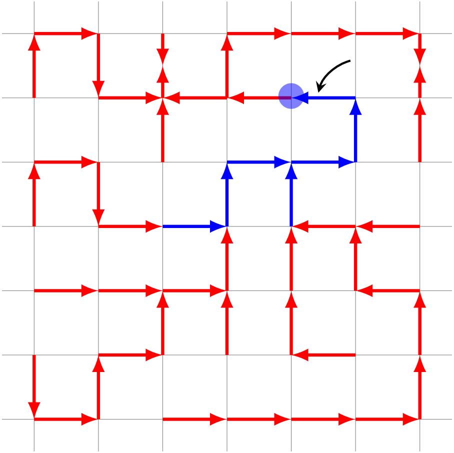
form a tree oriented toward the walker.

Why is USF$^+$ stationary from walker's POV?



The signposts at previously visited vertices
form a tree oriented toward the walker.

Why is USF$^+$ stationary from walker's POV?



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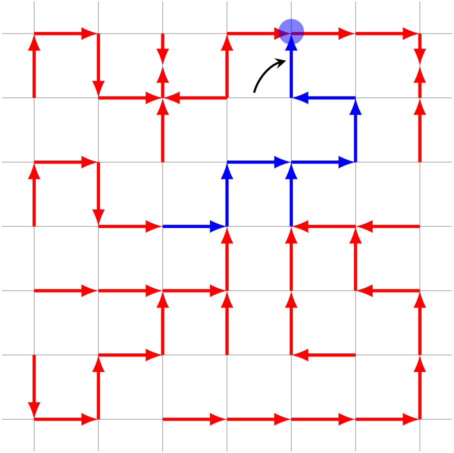

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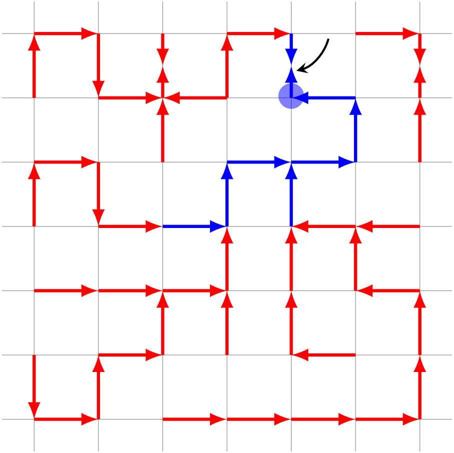
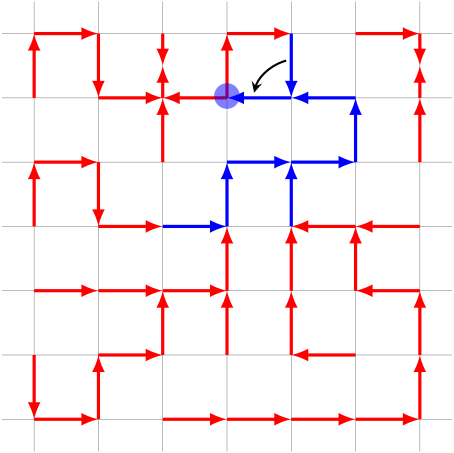
Why is USF^+ stationary from walker's POV?



The signposts at previously visited vertices form a tree oriented toward the walker.

Why is USF$^+$ stationary from walker's POV?



The signposts at previously visited vertices
form a tree oriented toward the walker.

Sketch of the scaling limit proof

Scaling limit

↑ **Martingale CLT**

Encounters vertical sign-posts half the time a.s.

↑ **Ergodic theorem**

Stationarity and ergodicity of USF^+ from walker's POV

So we have proved...

Theorem (C., Greco, Levine, Li '21)

Let $p = \frac{1}{2}$ *and let the uniform spanning forest plus one edge be the initial signpost configuration. Then, with probability 1, the p-rotor walk on* $\mathbb{Z}^2$ *scales to the standard 2-D Brownian motion:*

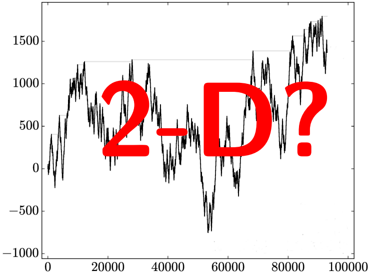
$$\frac{1}{\sqrt{n}}(\underbrace{X_{[nt]}}_{\substack{\text{location of the} \\ \text{walker at time } [nt]}})_{t\geq 0} \overset{n\to\infty}{\Longrightarrow} \frac{1}{\sqrt{2}}(\underbrace{B_1(t), B_2(t)}_{\substack{\text{independent} \\ \text{Brownian motions}}})_{t\geq 0}.$$

Open Problem

Problem

Find the scaling limit *for the p-rotor walk with i.i.d. uniform signpost configuration for* $p \neq \frac{1}{2}$.

Obstacle: Definition of "2-D perturbed Brownian motion (?)".

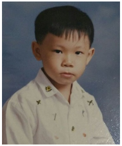


Back to our motivation

Well studied

Simple random walk

Know a little bit now



p-rotor walk

Many open problems

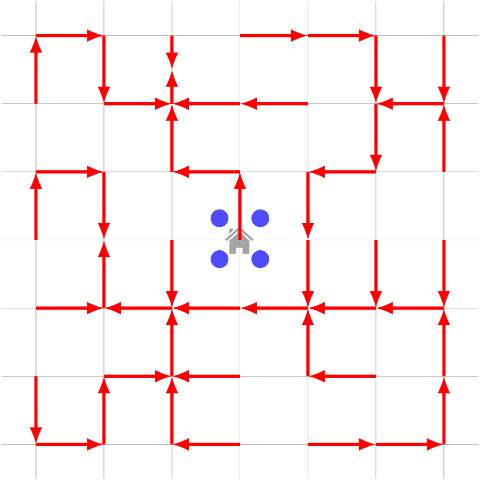
Rotor walk

Let's apply what we have learned back to rotor walk.

Escape rate of rotor walk

Prison break using rotor walk

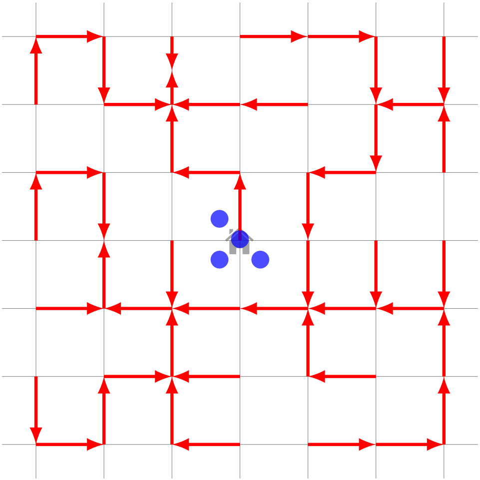
Put n walkers at the origin (the prison).



Note: signposts are never reset between iterations.

Prison break using rotor walk

First walker performs rotor walk, remove if returns to prison.



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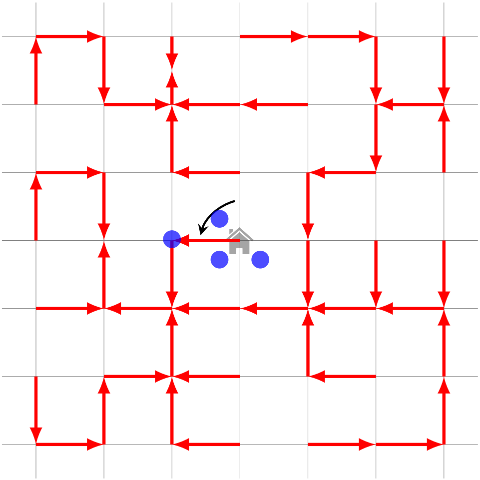

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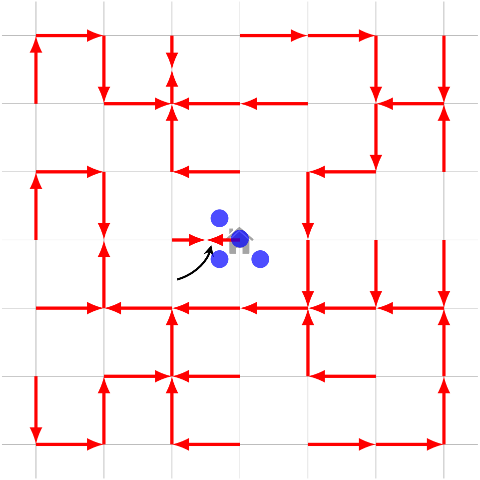
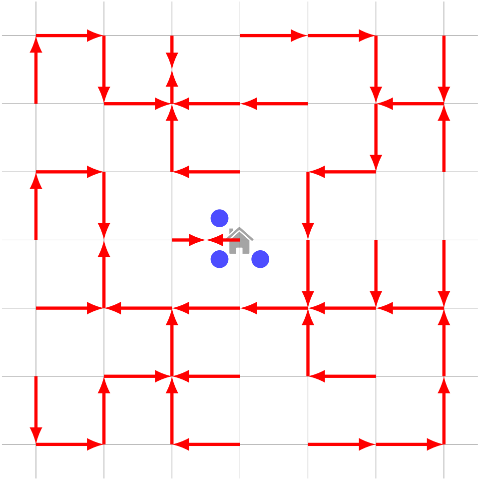


Note: signposts are never reset between iterations.

Prison break using rotor walk

First walker returns to prison, and is removed.



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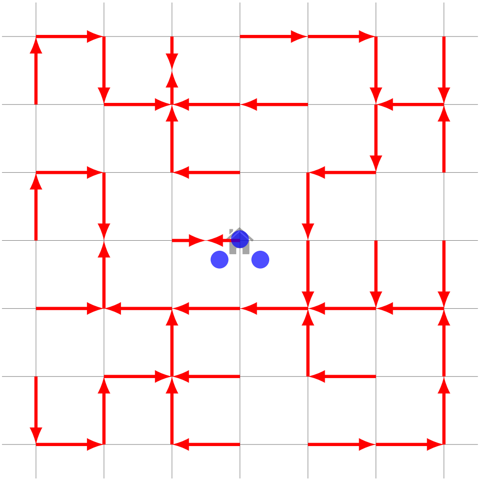

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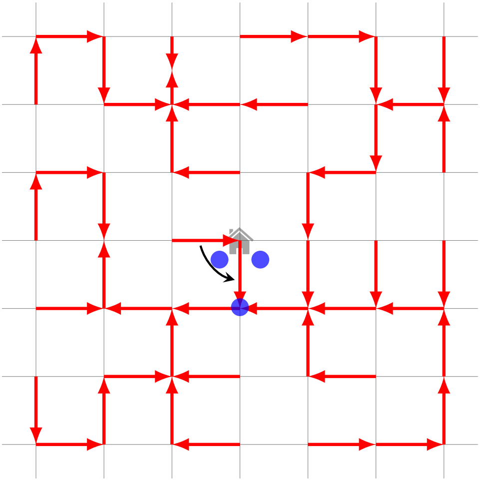

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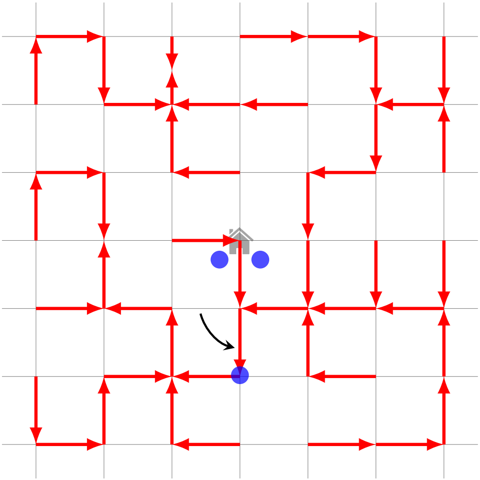

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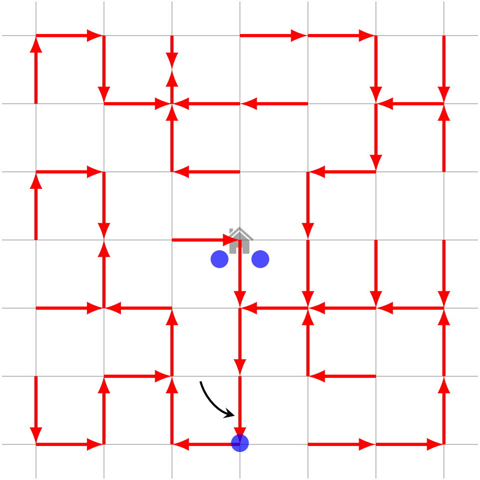

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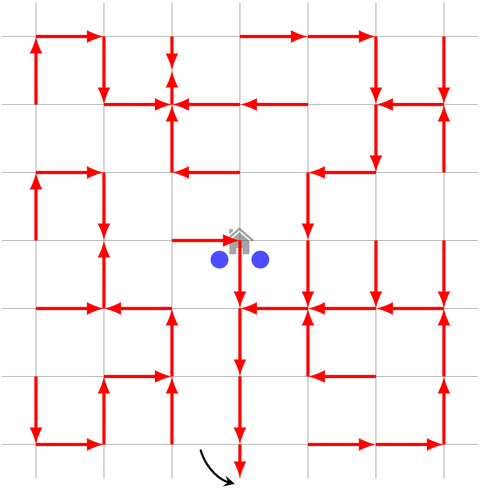

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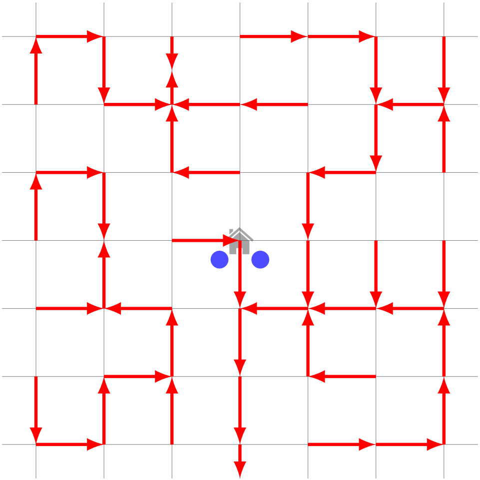
Prison break using rotor walk

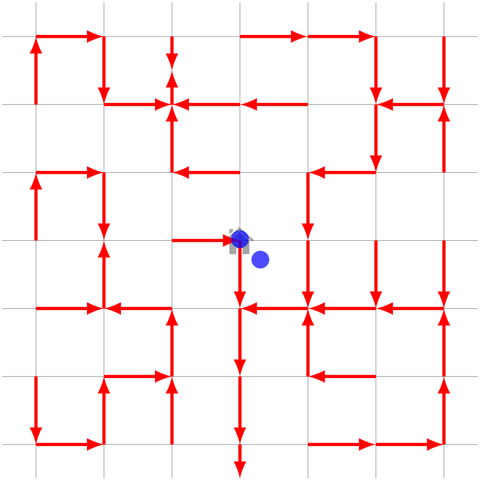
Second walker never returns to origin.



Note: signposts are never reset between iterations.

Prison break using rotor walk

Third walker performs rotor walk, remove if returns to prison.



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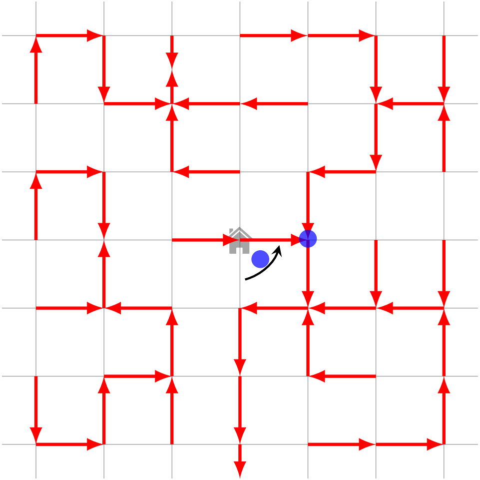

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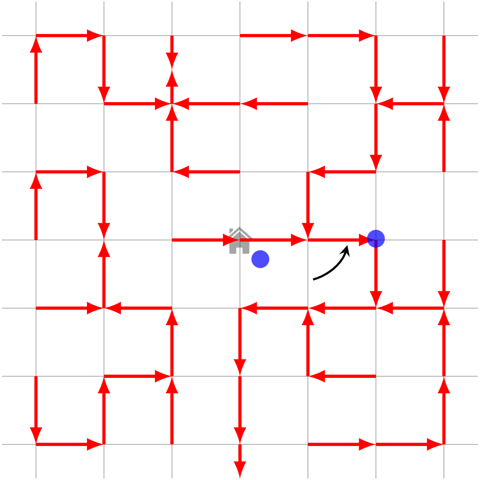

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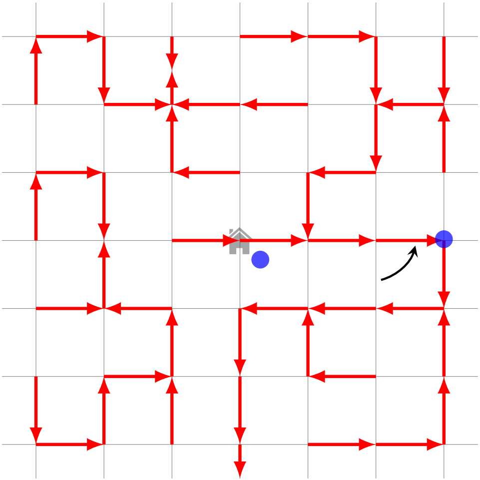

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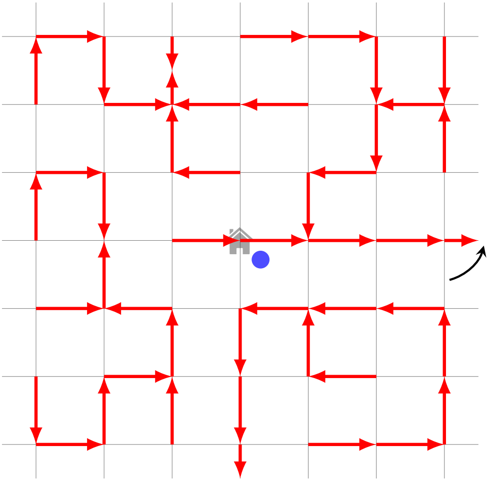
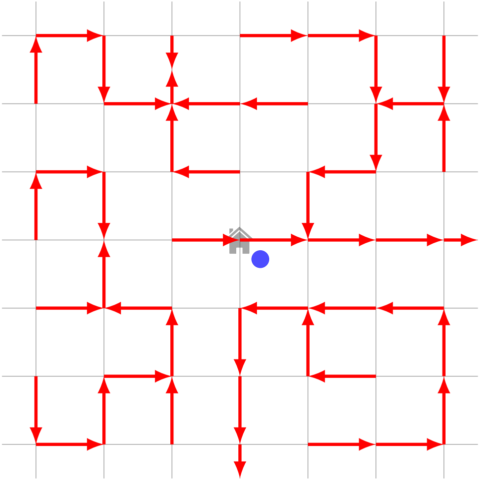


Note: signposts are never reset between iterations.

Prison break using rotor walk

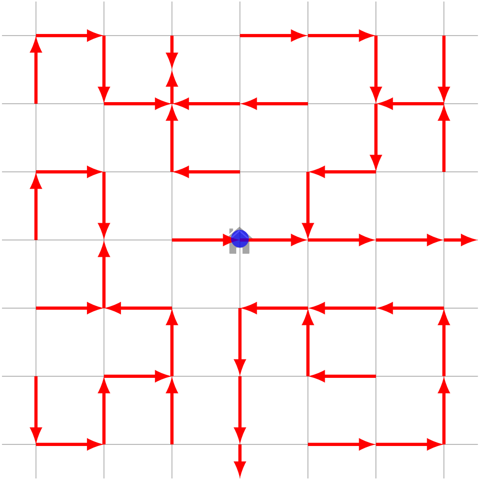
Third walker never returns to prison.



Note: signposts are never reset between iterations.

Prison break using rotor walk

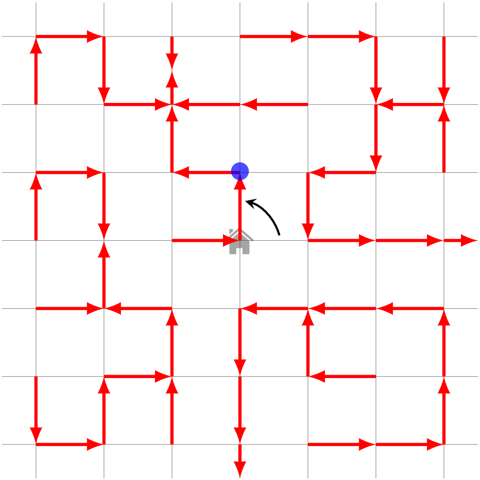
Fourth walker performs rotor walk, remove if returns to prison.



Note: signposts are never reset between iterations.

Prison break using rotor walk

Fourth walker performs rotor walk, remove if returns to prison.



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Prison break using rotor walk

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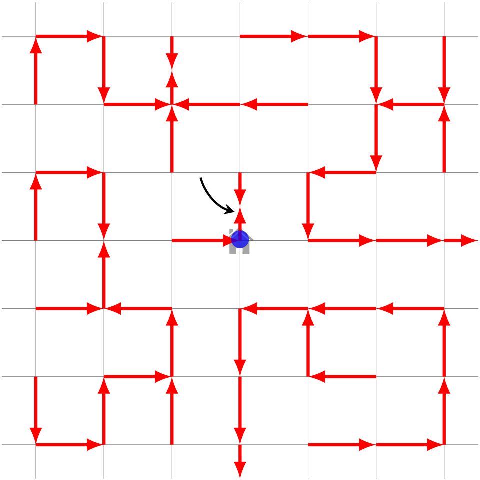

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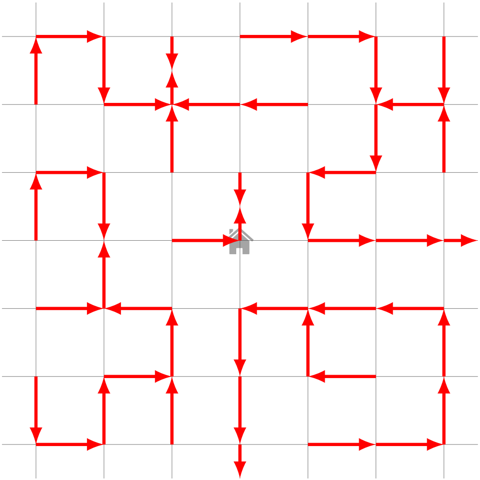
Prison break using rotor walk

Fourth alker returns to prison, and is removed.



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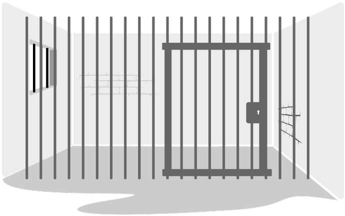
Escape rate of rotor walk



The escape rate of n rotor walkers with initial signpost ρ is

$$r_{\text{esc}}(\rho, n) := \frac{\text{number of escaped walkers}}{n}.$$

The escape rate of rotor walk is a deterministic counterpart of

$p_{\text{esc}}(\text{SRW}) :=$ Probability of simple random walk not returning to o,

the escape probability of simple random walk.

What was known about escape rate

Theorem (Schramm '10 (posthumous))

For *any* *initial signpost* ρ,

$$\limsup_{n\to\infty} r_{esc}(\rho, n) \quad \leq \quad p_{esc}(SRW).$$

Corollary

On $\mathbb{Z}^2$, *for* *any* *initial signpost* ρ,

$$\lim_{n\to\infty} r_{esc}(\rho, n) \; = \; p_{esc}(SRW) = 0.$$

In fact, this is true for all *recurrent* *graphs.*

What was known about escape rate

Theorem (Angel Holroyd '09)

On $\mathbb{Z}^d$ with $d \geq 3$, there exists an initial signpost ρ so that

$$\lim_{n\to\infty} r_{esc}(\rho, n) = 0.$$

Theorem (Florescu Ganguly Levine Peres '13)

On $\mathbb{Z}^d$ with $d \geq 3$, for the one-directional initial signpost ρ,

$$\liminf_{n\to\infty} r_{esc}(\rho, n) > 0.$$

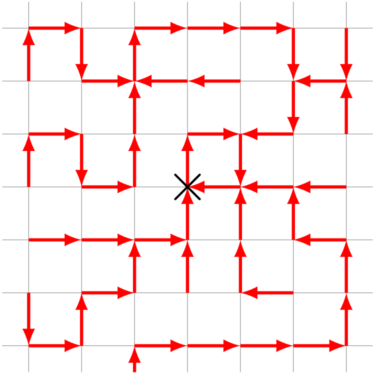
Escape rate conjecture

Conjecture (Florescu Ganguly Levine Peres '13)

For any transient graph, there exists an initial signpost ρ *for which*

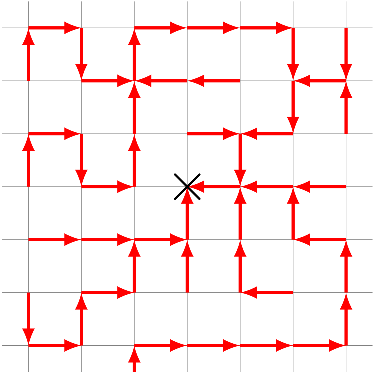
$$\lim_{n\to\infty} r_{esc}(\rho, n) \;=\; p_{esc}(SRW).$$

Uniform spanning forest oriented to infinity (USF^{∞})



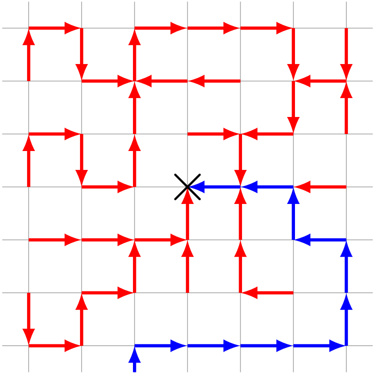
Start with uniform spanning forest plus one edge from before.

Uniform spanning forest oriented to infinity (USF^{∞})



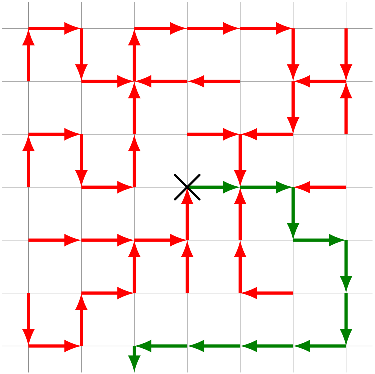
Remove the signpost at the origin.

Uniform spanning forest oriented to infinity (USF^∞)



Find the unique infinite path oriented to origin.

Uniform spanning forest oriented to infinity (USF^{∞})



Reverse the orientation of this infinite path.

Answering the escape rate conjecture

Theorem (C. '19)

On $\mathbb{Z}^d$, almost every ρ sampled from USF^∞ satisfies

$$\lim_{n\to\infty} r_{esc}(\rho, n) \;=\; p_{esc}(SRW).$$

Remark: Similar result applies to all vertex-transitive graphs.

Except that ...

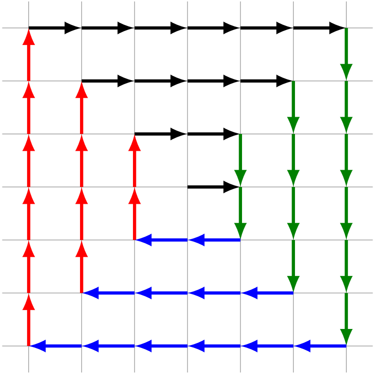
- The conjecture of FGLP '13 is for all transient graphs;
- There are already other constructions for the special case of $\mathbb{Z}^d$ (He '14) and trees (Angel Holroyd '11);
- Our construction of the initial signpost ρ is not deterministic.

Complete answer to the escape rate conjecture

Theorem (C., '20)

For any transient graph, the initial signpost $\rho_{\max}$ satisfies

$$\lim_{n\to\infty} r_{esc}(\rho_{\max}, n) \;=\; p_{esc}(SRW).$$



Escape rate formula

Lemma

For any initial signpost ρ and number of walkers n,

$$r_{esc}(\rho, n) = p_{esc}(SRW) - \sum_{x \in \mathbb{Z}^d} \left(\mathtt{w}_x[\underbrace{\rho_n(x)}_{\substack{\text{signpost at } x \\ \text{after } n\text{-th walk}}}] - \mathtt{w}_x[\underbrace{\rho(x)}_{\substack{\text{initial signpost} \\ \text{at } x}}] \right),$$

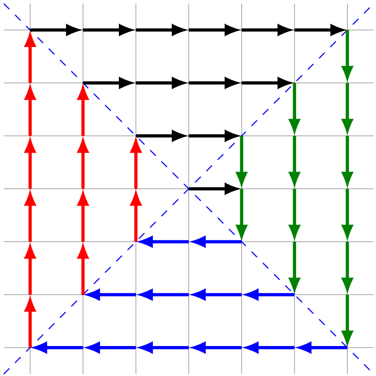
where $\mathtt{w}_x$ is a local compensator term.

The formula is inspired by the martingale used in proving recurrence for *p*-rotor walk.

Our initial signpost configuration

The configuration ρ_{max} is constructed by choosing, for each x,

the direction $\rho_{\text{max}}(x)$ that maximizes compensator $\mathtt{w}_x$.



Proof of the escape rate conjecture

- By the escape rate formula,

$$r_{\text{esc}}(\rho, n) \;=\; p_{\text{esc}}(SRW) - \sum_{x\in\mathbb{Z}^d} \Big(\mathtt{w}_x[\rho_n(x)] - \mathtt{w}_x[\rho(x)] \Big),$$

- By our choice of ρ_{max},

$$r_{\text{esc}}(\rho_{\text{max}}, n) \;\geq\; p_{\text{esc}}(SRW).$$

- On the other hand, Schramm's inequality gives us

$$\limsup_{n\to\infty} r_{\text{esc}}(\rho_{\text{max}}, n) \;\leq\; p_{\text{esc}}(SRW).$$

- Hence,

$$\lim_{n\to\infty} r_{\text{esc}}(\rho_{\text{max}}, n) \;=\; p_{\text{esc}}(SRW).$$

So we have proved...

Theorem (C., '20)

For any transient graph, the initial signpost $\rho_{\max}$ *satisfies*

$$\lim_{n\to\infty} r_{esc}(\rho_{\max}, n) \;=\; p_{esc}(SRW).$$

Open problem

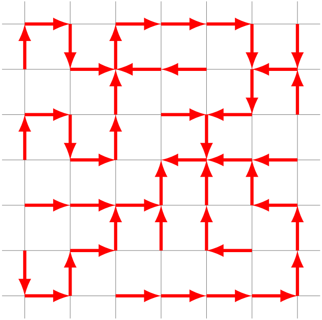
Conjecture

For any graph, the i.i.d. uniform signpost configuration has rotor walk escape rate equal to the escape probability of the SRW, i.e.,

$$\lim_{n\to\infty} r_{esc}(\rho, n) = p_{esc}(SRW).$$

Conjecture is known only for regular trees (Angel Holroyd '11).

THANK YOU!



Corresponding papers can be found in the webpage:

https://sites.math.rutgers.edu/~sc2518

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