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A simple proof of a recurrence theorem for random walks in $\mathbb{Z}^2$

Jean-Marc Derrien

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Abstract In this note, we prove without using Fourier analysis that the symmetric square integrable random walks in $\mathbb{Z}^2$ are recurrent.

George Pólya related in [3, pp. 582-583] an incident that enables him to formulate the question of recurrence for random walks: during a stroll through the woods, he felt embarrassed because he met “certainly much too often” a student with his girlfriend.

Let $x$ be an element of $\mathbb{Z}^2$. A random walk in $\mathbb{Z}^2$ starting at $x$ is a sequence $(S_n)_{n \in \mathbb{N}}$ of random variables such that

$$S_0 = x \quad \text{and} \quad S_n = x + X_1 + X_2 + \cdots + X_n, \quad n \in \mathbb{N},$$

where $(X_n)_{n \in \mathbb{N}}$ is a sequence of independent and identically distributed (i.i.d.), $\mathbb{Z}^2$-valued random variables. $(S_n)_{n \in \mathbb{N}}$ is characterized in law by $x$ and the law of $X_1$.

In this note, we give an elementary proof of the following result.

**Theorem** If $(S^{(1)}_n)_{n \in \mathbb{N}}$ and $(S^{(2)}_n)_{n \in \mathbb{N}}$ are two square integrable, independent and identically distributed random walks in $\mathbb{Z}^2$, then

$$S^{(1)}_n = S^{(2)}_n$$

infinitely often with probability one.

This theorem is a straightforward consequence of the following proposition (first proved in [2] in a more general context) applied to $(S_n := S^{(1)}_n - S^{(2)}_n)_{n \in \mathbb{N}}$.

**Proposition** If $(S_n)_{n \in \mathbb{N}}$ is a symmetric, square integrable random walk starting at 0 in $\mathbb{Z}^2$, then

$$S_n = 0$$

infinitely often with probability one.

**Proof** It is classical that, in order to prove this proposition, we have only to establish that

$$\sum_{n=0}^{+\infty} \mathbb{P}[S_n = 0] = +\infty$$

(see, for instance, [1]).

One can write

$$S_n = X_1 + X_2 + \cdots + X_n,$$

where $(X_k)_{k \geq 1}$ is a sequence of i.i.d., square integrable, $\mathbb{Z}^2$-valued random variables with $X_1 \equiv -X_1$ in distribution.
Since the square integrable random walk \((S_n)_{n \in \mathbb{N}}\) is symmetric, it is centered and we have

\[
\mathbb{E}(\|S_n\|_2^2) = \sum_{k=1}^n \mathbb{E}(\|X_k\|_2^2) + \sum_{1 \leq k < l \leq n} \mathbb{E}(X_k) \cdot \mathbb{E}(X_l) = n \mathbb{E}(\|X_1\|_2^2)
\]

(|| \cdot ||_2 denotes the euclidean norm).

The symmetry also gives

\[
\mathbb{P}[S_{2n} = 0] = \sum_{x \in \mathbb{Z}^2} \mathbb{P}[S_{2n} = 0 \mid S_n = x] \mathbb{P}[S_n = x] = \sum_{x \in \mathbb{Z}^2} \mathbb{P}\left[ -X_{n+1} - X_{n+2} - \cdots - X_{2n} = x \right] \mathbb{P}[S_n = x] = \sum_{x \in \mathbb{Z}^2} \mathbb{P}[S_n = x] \cdot \mathbb{P}[S_{2n} = 0].
\]

Hence if we introduce

\[
B_n := \{ x \in \mathbb{Z}^2 : \|x\|_2^2 < 2n \mathbb{E}(\|X_1\|_2^2) \},
\]

we deduce from Cauchy-Schwarz’s and Markov’s inequalities that, if \(n\) is large enough,

\[
\mathbb{P}[S_{2n} = 0] \geq \frac{1}{|B_n|} \left( \sum_{x \in B_n} \mathbb{P}[S_n = x] \right)^2 \geq \frac{C}{n} \left( 1 - \mathbb{P}[\|S_n\|_2^2 \geq 2n \mathbb{E}(\|X_1\|_2^2)] \right)^2 \geq \frac{C}{n} \left( 1 - \frac{\mathbb{E}(\|S_n\|_2^2)}{2n \mathbb{E}(\|X_1\|_2^2)} \right)^2 = \frac{C}{4n},
\]

where \(C > 0\) depends only on \(\mathbb{E}(\|X_1\|_2^2)\). The proposition follows.

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REFERENCES

