

Department of Mathematics

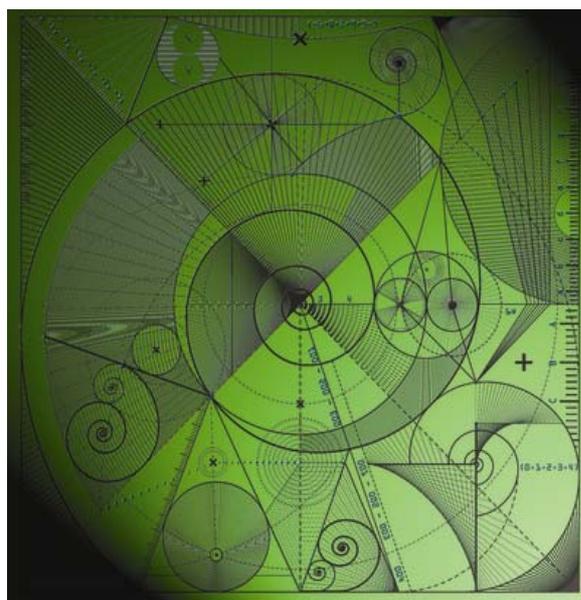
Preprint MPS_2010-08

20 March 2010

Eigenvalue problem meets Sierpinski
triangle: computing the spectrum of a non-
self-adjoint random operator

by

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Physicists have studied the operator A^b as the (non-self-adjoint) Hamiltonian of a particle hopping (asymmetrically) on a 1-dimensional lattice [15, 16, 9, 22]. Applications of such and related Hamiltonians, especially examples with random diagonals, include vortex line pinning in superconductors and growth models in population biology. The particular model (1) was proposed by Feinberg and Zee in [15], and some properties of its spectrum have been studied in [9, 22] (also see Paragraph 37, in particular Figure 37.7c, in [38]).

In all these studies the focus is on the case of a random sequence $b \in \{\pm 1\}^{\mathbb{Z}}$. A related but completely deterministic concept is that of a pseudo-ergodic sequence. In accordance with Davies [11], we call $b \in \{\pm 1\}^{\mathbb{Z}}$ *pseudo-ergodic* if every finite pattern of ± 1 's can be found somewhere (as a string of consecutive entries) in b . If b is pseudo-ergodic (which is almost surely the case if all b_k , $k \in \mathbb{Z}$, are independent (or at least not fully correlated) samples from a random variable with values in $\{\pm 1\}$ and nonzero probability for both $+1$ and -1) then, as a consequence of [7] (also see [6, 8, 29, 30] and cf. [11]), it holds that

$$\text{spec } A^b = \text{spec}_{\text{ess}} A^b = \bigcup_{c \in \{\pm 1\}^{\mathbb{Z}}} \text{spec } A^c = \bigcup_{c \in \{\pm 1\}^{\mathbb{Z}}} \text{spec}_{\text{point}}^{\infty} A^c. \quad (2)$$

The contribution of [7] is the third “=” sign in (2) that enables, or at least simplifies, the explicit computation of the spectra of particular pseudo-ergodic operators in [6, 8, 29]. The first “=” sign in (2) follows immediately from the second; the second comes from the Fredholm theory of much more general operators and is typically expressed in the language of so-called limit operators [34, 35, 27, 8]. (A similar equality, often with the closure taken of the union of spectra, can be found in the literature on spectral properties of Schrödinger and more general Jacobi operators [32, 4, 10, 11, 21, 1, 31, 17, 18, 19, 20, 33, 26, 25, 36, 37]. The three last papers also shed some light on the role of limit operators in the study of the absolutely continuous spectrum.)

Note that, by (2), the spectrum of A^b does not depend on the actual sequence b – as long as it is pseudo-ergodic. In [6] we obtain information about the spectrum, pseudospectrum and numerical range of the bi-infinite matrix operator A^b , its contraction A_+^b to the positive half axis (a semi-infinite matrix) and the finite sections A_n^b which, for $n \in \mathbb{N}$, are $n \times n$ submatrices of (1). Explicitly and precisely, these related matrices are

$$A_+^b = \begin{pmatrix} 0 & 1 & & & \\ b_1 & 0 & 1 & & \\ & b_2 & 0 & 1 & \\ & & b_3 & 0 & \ddots \\ & & & \ddots & \ddots \end{pmatrix} \quad \text{and} \quad A_n^b = \begin{pmatrix} 0 & 1 & & & \\ b_1 & 0 & 1 & & \\ & b_2 & 0 & \ddots & \\ & & \ddots & \ddots & 1 \\ & & & b_{n-1} & 0 \end{pmatrix},$$

where in the case $n = 1$ we set $A_1^b = (0)$. We explore in some detail in [6] the interrelations between the spectra and pseudospectra of A^b , A_+^b and A_n^b . Here, for $\varepsilon > 0$ and a bounded operator A on $\ell^2(\mathbb{N})$ or $\ell^2(\mathbb{Z})$, or on \mathbb{C}^n equipped with the 2-norm, we define the ε -pseudospectrum of A (see e.g. [2, 38]) by

$$\text{spec}_{\varepsilon} A := \{\lambda \in \mathbb{C} : \lambda \in \text{spec } A \text{ or } \|(A - \lambda I)^{-1}\| > 1/\varepsilon\},$$

where $\|\cdot\|$ is the induced operator norm. It is convenient also to use the notation $\text{spec}_0 A := \text{spec } A$. Note that the finite matrix A_n^b only depends on the $n - 1$ values $b_1, \dots, b_{n-1} \in \{\pm 1\}$. Recognising this, we will use the notation $A_n^{b'}$, where $b' = (b_1, \dots, b_{n-1}) \in \{\pm 1\}^{n-1}$, as an alternative notation for the same matrix A_n^b .

Here is a summary of our results from [6]:

Theorem 1.1 [6] *If $b \in \{\pm 1\}^{\mathbb{Z}}$ is pseudo-ergodic (which holds almost surely if b is random in the sense discussed above) then the following statements hold.*

- a) $\text{spec } A^b$ is invariant under reflection about either axis as well as under a 90° rotation around the origin.

- b) Provided the “positive” part of the sequence b (by which we mean $(b_k)_{k \in \mathbb{N}}$) is itself pseudo-ergodic (contains every finite pattern of ± 1 ’s), then, for all $\varepsilon \geq 0$ one has

$$\text{spec}_\varepsilon A^b = \text{spec}_\varepsilon A^b_+.$$

- c) The numerical range of A^b (considered as an operator on $\ell^2(\mathbb{Z})$) is

$$W(A^b) = \{x + iy : x, y \in \mathbb{R}, |x| + |y| < 2\},$$

and $\text{spec } A^b$ is a strict subset of the closure, $\text{clos}(W(A^b))$, of the numerical range, so that

$$\text{spec } A^b \subsetneq \{x + iy : x, y \in \mathbb{R}, |x| + |y| \leq 2\}.$$

- d) For every $n \in \mathbb{N}$, where $\Pi_n := \{c \in \{\pm 1\}^{\mathbb{Z}} : c \text{ is } n\text{-periodic}\}$, the set

$$\pi_n := \bigcup_{c \in \Pi_n} \text{spec } A^c = \bigcup_{c \in \Pi_n} \text{spec}_{\text{point}}^\infty A^c \quad (3)$$

is contained in $\text{spec } A^b$, by (2). Each set π_n consists of $k \in \{\frac{2^n}{n}, \dots, 2^n\}$ analytic arcs (see Figure 1.1) that can be computed explicitly (as unions of sets of eigenvalues of $n \times n$ matrices). In particular,

$$\pi_1 = [-2, 2] \cup [-2i, 2i] \quad \text{and} \quad \pi_2 = \pi_1 \cup \{x + iy : -1 \leq x \leq 1, y = \pm x\}.$$

- e) For all $n \in \mathbb{N}$ and $\varepsilon \geq 0$, the set

$$\sigma_{n,\varepsilon} := \bigcup_{c \in \{\pm 1\}^{n-1}} \text{spec}_\varepsilon A_n^c \quad (4)$$

is contained in $\text{spec}_\varepsilon A^b$ (see Figure 1.2 for $\varepsilon = 0$).

- f) In the case of spectra ($\varepsilon = 0$), the finite matrix eigenvalues $\sigma_n := \sigma_{n,0}$ from (4) are connected with the periodic operator spectra π_n from (3) by

$$\sigma_n \subset \pi_{2n+2} \subset \text{spec } A^b \quad (5)$$

for all $n \in \mathbb{N}$ (see Figure 2.1).

- g) As a special case of a much more general spectral inclusion result from [5], we can complement the inclusion $\sigma_{n,\varepsilon} \subset \text{spec}_\varepsilon A^b$ from e) by

$$\sigma_{n,\varepsilon} \subset \text{spec}_\varepsilon A^b \subset \sigma_{n,\varepsilon+\varepsilon_n} \quad \text{and} \quad \sigma_n \subset \text{spec } A^b \subset \text{clos}(\sigma_{n,\varepsilon_n}),$$

for $n \in \mathbb{N}$ and $\varepsilon > 0$, where $\varepsilon_n = 4 \sin \theta_n < 2\pi/(n+1)$, with θ_n the unique solution in the interval $\left(\frac{\pi}{2(n+3)}, \frac{\pi}{2(n+1)}\right)$ of the equation

$$2 \cos((n+1)\theta) = \cos((n-1)\theta).$$

Remark 1.2 Note that the right “=” sign in (3) holds because $\text{spec } A^c = \text{spec}_{\text{point}}^\infty A^c$ for all periodic sequences c , whereas the right “=” sign in (2) only holds as stated, with the union taken over all $c \in \{\pm 1\}^{\mathbb{Z}}$; the spectrum and point spectrum of A^c are different, in general, for specific $c \in \{\pm 1\}^{\mathbb{Z}}$. \square

Remark 1.3 Regarding the bounds in g), note that these imply that $\text{spec } A^b \subset \text{clos}(\sigma_{n,\varepsilon_n}) \subset \text{clos}(\text{spec}_{\varepsilon_n} A^b)$. Since $\varepsilon_n \rightarrow 0$ so that [38] $\text{clos}(\text{spec}_{\varepsilon_n} A^b) \rightarrow \text{spec } A^b$ in the Hausdorff metric as $n \rightarrow \infty$, it follows that $\text{clos}(\sigma_{n,\varepsilon_n}) \rightarrow \text{spec } A^b$ as $n \rightarrow \infty$. For small values of n the upper bound $\text{clos}(\sigma_{n,\varepsilon_n})$ can be evaluated very explicitly. In particular, $\theta_1 = \pi/6$ so that $\varepsilon_1 = 2$ and, since $A_1^c = (0)$, we obtain that $\text{spec } A^b \subset \text{clos}(\sigma_{1,\varepsilon_1}) = \{\lambda \in \mathbb{C} : |\lambda| \leq 2\}$. The result in c) above, that $\text{spec } A^b$ is a strict subset of the numerical range, comes from the bound in g) applied with $n = 34$, when σ_{n,ε_n} is the union of the pseudospectra of $2^{33} \approx 8.6 \times 10^9$ matrices of size 34×34 . \square

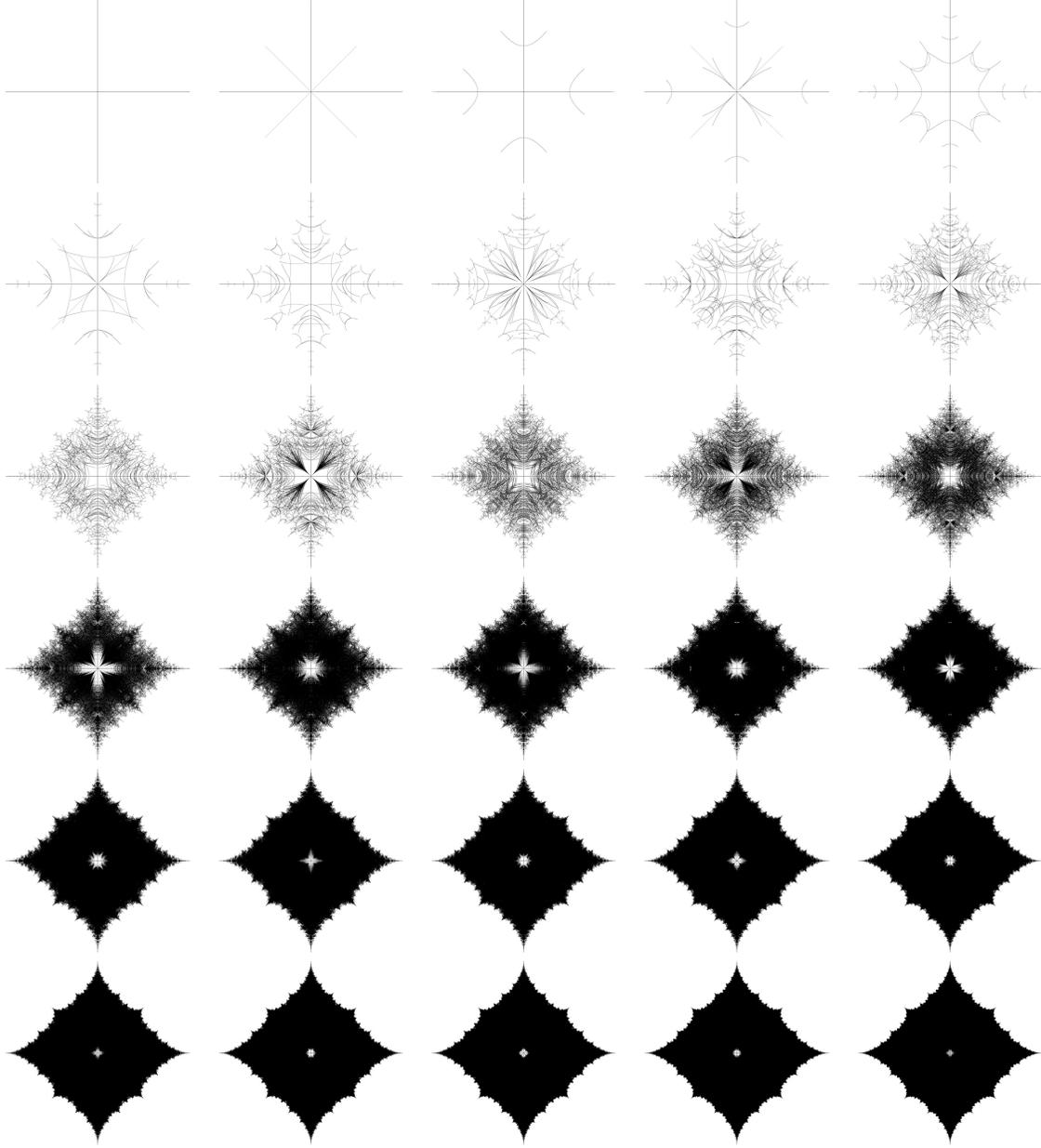


Figure 1.1: Our figure shows the sets π_n , as defined in (3), for $n = 1, \dots, 30$. Recall that $\pi_1 = [-2, 2] \cup [-2i, 2i]$ and that, for each n , $\pi_1 \subset \pi_n \subset \{x + iy : x, y \in \mathbb{R}, |x| + |y| \leq 2\}$. Note also that spectra of periodic infinite matrices can be expressed analytically (by Fourier transform techniques, see e.g. [3, 12]) and that each set π_n consists of k analytic arcs, where $2^n/n \leq k \leq 2^n$.

It follows from Theorem 1.1 d) and e) that both

$$\sigma_\infty := \bigcup_{n=1}^{\infty} \sigma_n \quad \text{and} \quad \pi_\infty := \bigcup_{n=1}^{\infty} \pi_n$$

are subsets of $\text{spec } A^b$ (with, by f), $\sigma_\infty \subset \pi_\infty$). These subsets consist of countably many points and countably many analytic arcs, respectively, and so both have zero (two-dimensional) Lebesgue measure. Indeed, it is not clear from any of the results in Theorem 1.1 (or other results in the

literature) whether $\text{spec } A^b$ has positive Lebesgue measure, in particular whether it has interior points. Related to this question, Holz et al. [22, Sections I, V, VI], conjecture that $\text{clos}(\sigma_\infty) \subset \text{spec } A^b$ has a fractal dimension in the range $(1, 2)$, and so has zero Lebesgue measure.

The purpose of the current paper is to shed light on these questions by constructing a sequence $c \in \{\pm 1\}^{\mathbb{Z}}$ for which $\text{spec}_{\text{point}}^\infty A^c$ contains the open unit disk. As a consequence of formula (2) and the closedness of spectra, this shows that $\text{spec } A^b$ contains the closed unit disk and therefore has dimension 2 and a positive Lebesgue measure. This is the main result of the next section. Intriguingly we will see that the sequence constructed, while rather irregular, is such that each λ in the unit disk is an eigenvalue of A^c in $\ell^\infty(\mathbb{Z})$, and with a vector whose components are polynomials in λ with coefficients forming the regular self-similar pattern of a discrete Sierpinski triangle.

We will finish the paper with our own conjecture on the geometry of $\text{clos}(\sigma_\infty)$ and $\text{spec } A^b$.

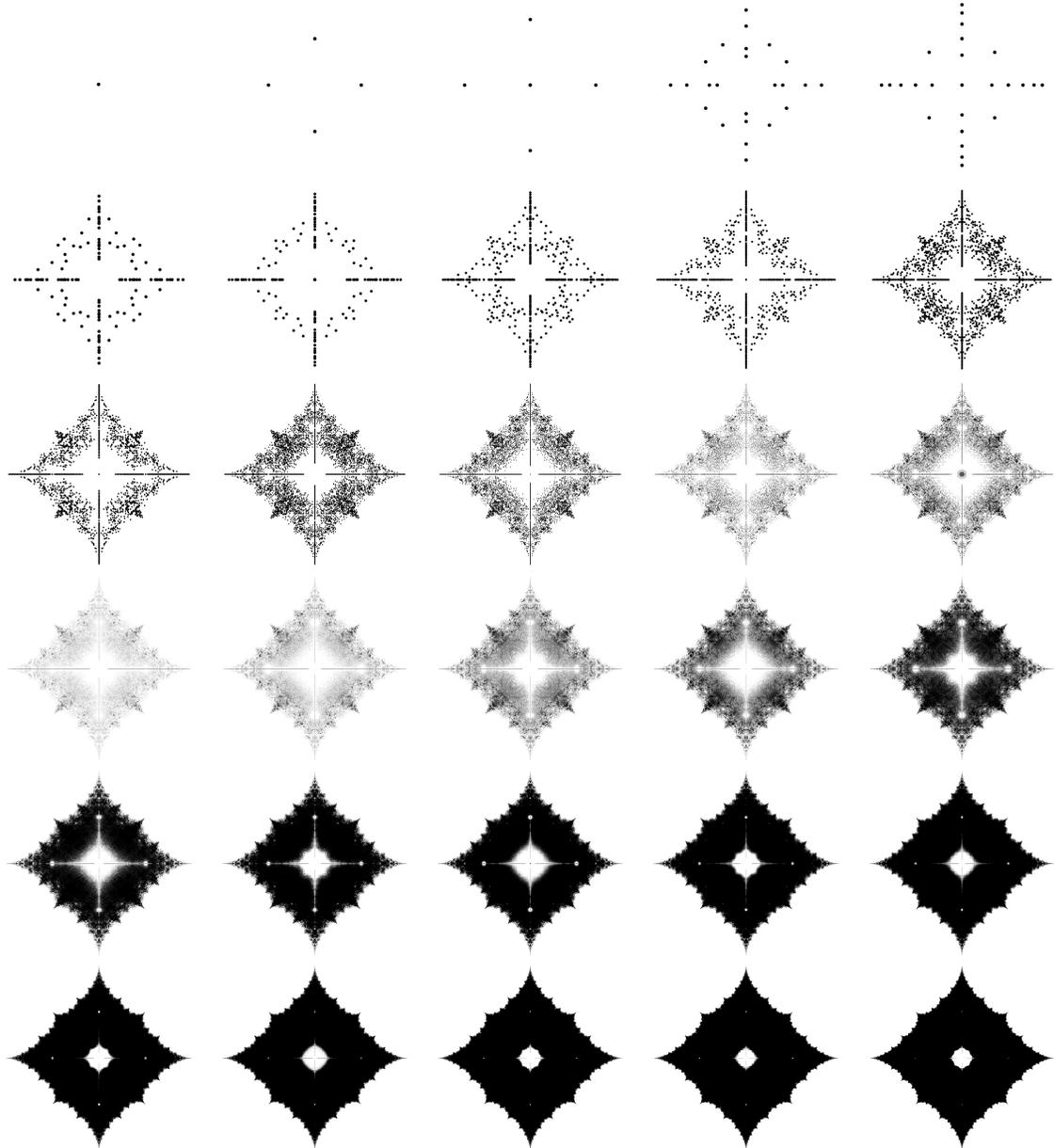


Figure 1.2: Our figure shows the sets $\sigma_n := \sigma_{n,0}$ of all $n \times n$ matrix eigenvalues, as defined in (4), for $n = 1, \dots, 30$. Note that in the first pictures (with only a few eigenvalues), we have used heavier pixels for the sake of visibility. By (5), each of the sets with $n = 1, 2, \dots, 14$ in this figure is contained, respectively, in the set number $2n + 2$ of Figure 1.1.

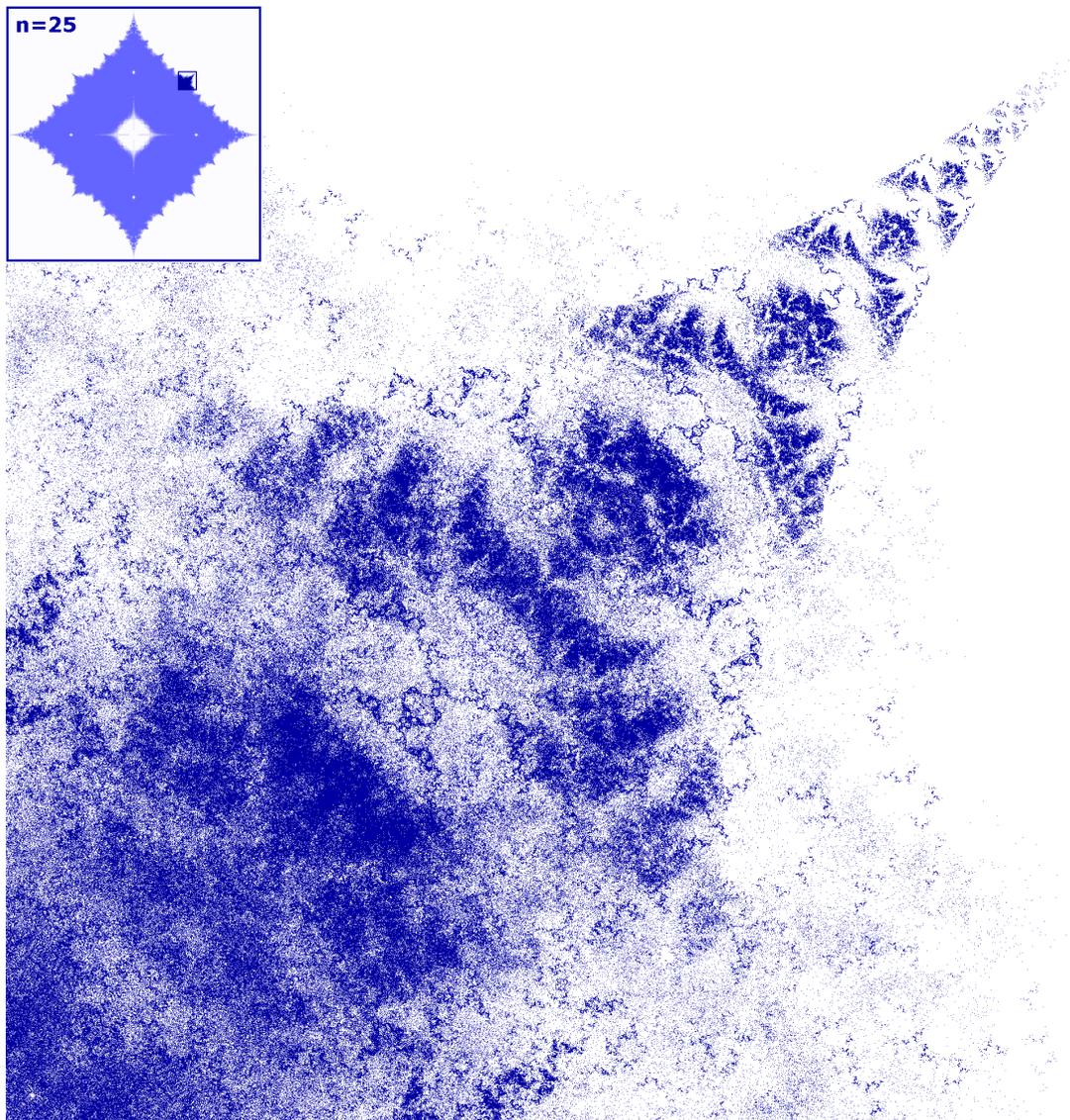


Figure 1.3: This is a zoom into σ_{25} – the 25th picture of Figure 1.2. The location of this zoom is near the point $1 + i$, which is the midpoint of the northeast edge of the square $\text{clos}(W(A^b)) = \text{conv}\{2, -2, 2i, -2i\}$. The picture clearly suggests self-similar features of the set σ_{25} .

2 A sequence c for which $\text{spec } A^c$ contains the unit disk

The formula (2) for the spectrum of A^b when $b \in \{\pm 1\}^{\mathbb{Z}}$ is pseudo-ergodic motivates the following approach to decide whether a given point $\lambda \in \mathbb{C}$ is in $\text{spec } A^b$ or not: look for a sequence $c \in \{\pm 1\}^{\mathbb{Z}}$ such that $\lambda \in \text{spec}_{\text{point}}^{\infty} A^c$, in other words, such that there exists a non-zero $u \in \ell^{\infty}(\mathbb{Z})$ with

$A^c u = \lambda u$, i.e.

$$u_{i+1} = \lambda u_i - c_i u_{i-1} \tag{6}$$

for $i \in \mathbb{Z}$. If such a sequence c exists then $\lambda \in \text{spec } A^b$ – if not, then not.

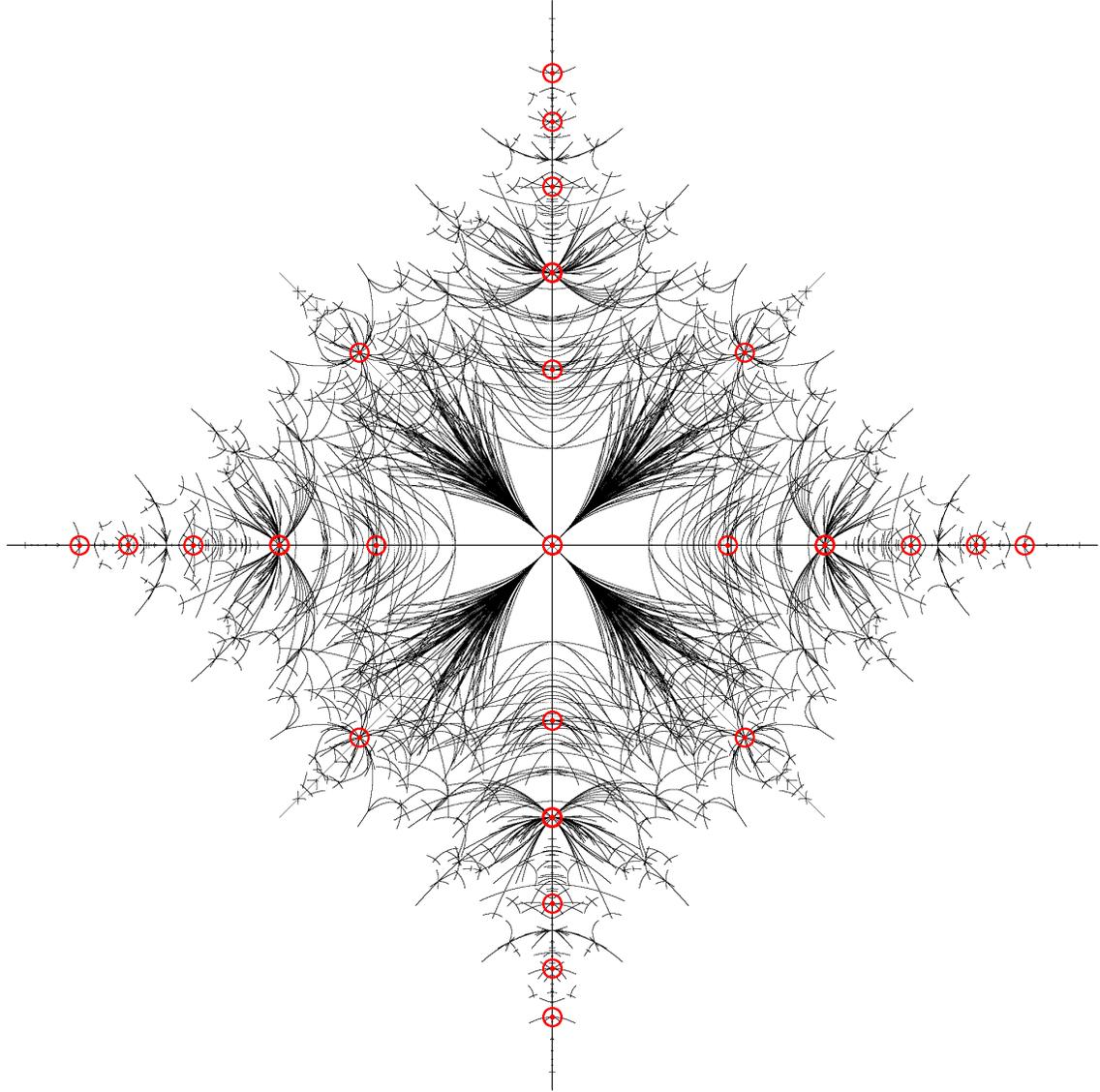


Figure 2.1: Here we see the inclusion $\sigma_5 \subset \pi_{12}$, which holds by (5) with $n = 5$. (The points in σ_5 are indicated by circled dots.)

Starting from $u_0 = 0$ and $u_1 = 1$, we will successively use (6) to compute u_i for $i = 2, 3, \dots$ (an analogous procedure is possible for $i = -1, -2, -3, \dots$) and see whether the sequence remains bounded. Doing so, we get

$$\begin{aligned} u_2 &= \lambda, & u_3 &= \lambda^2 - c_2, & u_4 &= \lambda^3 - (c_2 + c_3)\lambda, \\ u_5 &= \lambda^4 - (c_2 + c_3 + c_4)\lambda^2 + c_2 c_4, \end{aligned}$$

Proposition 2.1 Define the sequence $c \in \{\pm 1\}^{\mathbb{Z}}$, for positive indices by $c_1 = 1$ and by the requirement that

$$c_{2i} = c_{2i-1} c_i \quad \text{and} \quad c_{2i+1} = -c_{2i}, \quad i = 1, 2, \dots,$$

and for non-positive indices by

$$c_{-i} = c_{i+1}, \quad i = 0, 1, \dots$$

Further, given $\lambda \in \mathbb{C}$, define the sequence $u = (u_i)_{i \in \mathbb{Z}}$, by the requirement that

$$u_{i+1} = \lambda u_i - c_i u_{i-1}, \quad i \in \mathbb{Z},$$

and by the initial conditions

$$u_0 = 0, \quad u_1 = 1.$$

Then, as a function of λ , for $i \in \mathbb{Z}$, u_i is a polynomial of degree $|i| - 1$ with all its coefficients taking values in the set $\{-1, 0, 1\}$.

In more detail, denoting, for $i, j \in \mathbb{N}$, the coefficient of λ^{j-1} in the polynomial u_i by $p_{i,j}$, the following statements hold.

(i) $p_{i,j} = 0$ for $j > i$, so that, for every $i \in \mathbb{N}$,

$$u_i = \sum_{j=1}^i p_{i,j} \lambda^{j-1}.$$

(ii) Defining, additionally, $p_{i,j} := 0$ if $i, j \in \mathbb{N} \cup \{0\}$ and $i = 0$ or $j = 0$, it holds that $p_{1,1} = 1$ and that

$$p_{i+1,j} = p_{i,j-1} - c_i p_{i-1,j}, \quad (10)$$

for $i \in \mathbb{N}$ and $j = 1, 2, \dots, i+1$.

(iii) $p_{i,j} = 0$ if $i+j$ is odd.

(iv) Writing the semi-infinite coefficient matrix $P = (p_{i,j})_{i,j \in \mathbb{N}}$ in block form as $P = (\mathbf{p}_{i,j})_{i,j \in \mathbb{N}}$ where, for $i, j \in \mathbb{N}$,

$$\mathbf{p}_{i,j} := \begin{pmatrix} p_{2i-1,2j-1} & p_{2i-1,2j} \\ p_{2i,2j-1} & p_{2i,2j} \end{pmatrix},$$

it holds, for $i \in \mathbb{N}$, that $\mathbf{p}_{i,j} = 0$ for $j > i$ while, for $j = 1, \dots, i$,

$$\mathbf{p}_{i,j} = \begin{cases} p_{i,j} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, & \text{if } i+j \text{ is even,} \\ c_{2i-1} p_{i-1,j} \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, & \text{if } i+j \text{ is odd.} \end{cases} \quad (11)$$

(v) $p_{i,j} \in \{-1, 0, 1\}$ for $i, j \in \mathbb{N}$.

(vi) Let $V := \{(0, 0), (-1, -1), (1, -1)\}$ and let $S := \{(i, j) \in \mathbb{N}^2 : p_{i,j} \text{ is non-zero}\}$. Let $\Sigma := 2^{\mathbb{N}^2}$ be the set of all subsets of \mathbb{N}^2 , and define $\mathbf{T} : \Sigma \rightarrow \Sigma$ by

$$\mathbf{T}(\sigma) = 2\sigma + V := \{a + b : a \in \sigma, b \in V\}, \quad \text{for } \sigma \in \Sigma.$$

Then, where

$$S_1 := \{(1, 1)\}, \quad \text{and } S_{n+1} := \mathbf{T}(S_n), \quad n \in \mathbb{N},$$

it holds that

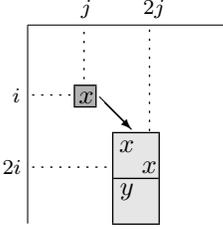
$$S = \bigcup_{n \in \mathbb{N}} S_n \quad \text{and that} \quad S = \mathbf{T}(S).$$

(vii) For $i \in \mathbb{N} \cup \{0\}$,

$$u_{-i} = d_i u_i,$$

where, for $j \in \mathbb{N} \cup \{0\}$,

$$d_{2j} := (-1)^j c_{2j}, \quad d_{2j+1} := (-1)^{j+1}.$$



Remark 2.2 Statements (iv) and (vi) reveal the self-similar nature of the pattern (7). With respect to a scaling of the pattern by the factor 2, an entry $p_{i,j}$, with $i+j$ even, replicates three times: as $p_{2i-1,2j-1}$, $p_{2i,2j}$ and, multiplied by c_{2i+1} , as $p_{2i+1,2j-1}$. So the “volume” of the pattern (7) triples under a scaling by 2, which is why (see [13]) its zeta dimension is $\log_2 3 \approx 1.585$ – exactly the fractal (Hausdorff or packing) dimension of its bounded version, the usual Sierpinski triangle or gasket [14]. \square

As an immediate consequence of Proposition 2.1 and formula (2) we get our main result.

Theorem 2.3 For the sequence $c \in \{\pm 1\}^{\mathbb{Z}}$ from Proposition 2.1, it holds that the closed unit disk $\overline{\mathbb{D}} := \{z \in \mathbb{C} : |z| \leq 1\}$ is contained in $\text{spec } A^c$. Consequently, for a pseudo-ergodic $b \in \{\pm 1\}^{\mathbb{Z}}$, one has $\overline{\mathbb{D}} \subset \text{spec } A^b$, so that $\text{spec } A^b$ has dimension 2 and positive Lebesgue measure.

Proof. Let $\lambda \in \mathbb{D} := \{z \in \mathbb{C} : |z| < 1\}$, let c be the sequence from Proposition 2.1 and $u : \mathbb{Z} \rightarrow \mathbb{C}$ the eigenfunction from (6). Then, for every $i \in \mathbb{N}$,

$$|u_{-i}| = |u_i| = \left| \sum_{j=1}^i p_{i,j} \lambda^{j-1} \right| \leq \sum_{j=1}^i |p_{i,j}| |\lambda|^{j-1} \leq \sum_{j=1}^{\infty} |\lambda|^{j-1} = \frac{1}{1-|\lambda|},$$

showing that $u \in \ell^\infty(\mathbb{Z})$, and, by our construction (6), $A^c u = \lambda u$. So $\mathbb{D} \subset \text{spec}_{\text{point}}^\infty A^c \subset \text{spec } A^c$. Since $\text{spec } A^c$ is closed, it holds that $\overline{\mathbb{D}} \subset \text{spec } A^c$. The claim for a pseudo-ergodic b now follows from $\text{spec } A^c \subset \text{spec } A^b$, by (2). Finally, from the monotonicity of (all notions of) dimension [14], $2 = \dim(\overline{\mathbb{D}}) \leq \dim(\text{spec } A^b) \leq \dim(\mathbb{R}^2) = 2$. \blacksquare

Proof of Proposition 2.1. Statements (i) and (ii) are clear from the discussion preceding Proposition 2.1, and statement (iii) then follows easily by induction. Thus $\mathbf{p}_{i,j} = 0$ for $j > i$, and in every matrix $\mathbf{p}_{i,j}$ the off-diagonal entries are zero, i.e. $p_{2i-1,2j} = 0 = p_{2i,2j-1}$ for all i, j .

We will now prove (iv) by proving by induction that, for each $i \in \mathbb{N}$, (11) holds for $j = 1, \dots, i$. It is easy to check that (11) holds for $i = j = 1$. Now suppose that, for some $k \in \mathbb{N}$, (11) holds for $i = 1, \dots, k$, $j = 1, \dots, i$. We will show that this implies that (11) holds for $i = k+1$ and $j = 1, \dots, k+1$.

We let $i = k+1$ and start with the case when $i+j$ is even. By (10) we have that

$$\begin{aligned} p_{2i-1,2j-1} &= p_{2i-2,2j-2} - c_{2i-2} p_{2i-3,2j-1} \\ &= p_{2(i-1),2(j-1)} - c_{2i-2} p_{2(i-1)-1,2j-1}, \end{aligned} \tag{12}$$

with $p_{2(i-1),2(j-1)} = p_{i-1,j-1} = 0$ if $j = 1$ and, by the inductive hypothesis (and since $i-1+j-1$ is even), $p_{2(i-1),2(j-1)} = p_{i-1,j-1}$ if $j > 1$. Also, by the inductive hypothesis, $p_{2(i-1)-1,2j-1} = c_{2(i-1)-1} p_{i-2,j}$ since $i-1+j$ is odd, while, from the definition of the sequence c , $c_{2i-2} = c_{2i-3} c_{i-1}$. Inserting these results in (12), we get that

$$\begin{aligned} p_{2i-1,2j-1} &= p_{i-1,j-1} - c_{2i-3} c_{i-1} c_{2i-3} p_{i-2,j} \\ &= p_{i-1,j-1} - c_{i-1} p_{i-2,j} = p_{i,j}, \end{aligned} \tag{13}$$

by (10). We have observed already that $p_{2i-1,2j} = 0 = p_{2i,2j-1}$ for all i, j , so it remains to consider $p_{2i,2j}$. By (10), (13), and the inductive hypothesis which implies that $p_{2i-2,2j} = p_{2(i-1),2j} = 0$ as $i-1+j$ is odd, we have that

$$p_{2i,2j} = p_{2i-1,2j-1} - c_{2i-1} p_{2i-2,2j} = p_{i,j}.$$

Now suppose $i + j$ is odd. Then, by (10) and the inductive hypothesis,

$$\begin{aligned} p_{2i-1,2j-1} &= p_{2i-2,2j-2} - c_{2i-2} p_{2i-3,2j-1} \\ &= 0 - c_{2i-3} c_{i-1} p_{i-1,j} = c_{2i-1} p_{i-1,j}, \end{aligned}$$

since $c_{2i-1} = -c_{2i-2} = -c_{2i-3} c_{i-1}$. By (10) and the inductive hypothesis and noting that $i - 1 + j$ is even,

$$\begin{aligned} p_{2i,2j} &= p_{2i-1,2j-1} - c_{2i-1} p_{2i-2,2j} \\ &= c_{2i-1} p_{i-1,j} - c_{2i-1} p_{i-1,j} = 0. \end{aligned}$$

This completes the proof of (iv), and (v) follows from (iv) by a simple induction argument.

To see that (vi) is true, observe first that, from (i), (iii), and (iv) (and cf. Remark 2.2), it holds for $i', j' \in \mathbb{N}$ that $(i', j') \in S$ iff, for some $i, j \in \mathbb{N}$ either (a) $(i', j') = (2i, 2j)$ and $(i, j) \in S$; or (b) $(i', j') = (2i - 1, 2j - 1)$ and $(i, j) \in S$ or $(i - 1, j) \in S$. From this it follows that $S = \mathbf{T}(S)$.

Define a metric d on Σ by

$$d(\sigma, \tau) := \sum_{(i,j) \in (\sigma \cup \tau) \setminus (\sigma \cap \tau)} 2^{-i-j}, \quad \sigma, \tau \in \Sigma.$$

Then

$$\begin{aligned} d(\mathbf{T}(\sigma), \mathbf{T}(\tau)) &\leq \sum_{(i,j) \in (\sigma \cup \tau) \setminus (\sigma \cap \tau)} \left(2^{-2i-2j} + 2^{-(2i-1)-(2j-1)} + 2^{-(2i+1)-(2j-1)} \right) \\ &= \sum_{(i,j) \in (\sigma \cup \tau) \setminus (\sigma \cap \tau)} 2^{-i-j} (2^{-i-j} + 2^{2-i-j} + 2^{-i-j}) \leq \frac{3}{4} d(\sigma, \tau), \end{aligned} \quad (14)$$

if $(1, 1) \notin (\sigma \cup \tau) \setminus (\sigma \cap \tau)$. Let $\Sigma_1 := \{\sigma \in \Sigma : (1, 1) \in \sigma\}$. Then $\mathbf{T}(\Sigma_1) \subset \Sigma_1$ and, by (14), \mathbf{T} is a contraction mapping on Σ_1 . Thus, by the contraction mapping theorem, \mathbf{T} has a unique fixed point in Σ_1 , which is the set S , and, if $\sigma_1 \in \Sigma_1$ and $\sigma_{n+1} := \mathbf{T}(\sigma_n)$, $n \in \mathbb{N}$, then $d(\sigma_n, S) \rightarrow 0$ as $n \rightarrow \infty$. In particular, $d(S_n, S) \rightarrow 0$ as $n \rightarrow \infty$. Since also (by an easy induction argument) $S_1 \subset S_2 \subset \dots$, it follows that $S = \cup_{n \in \mathbb{N}} S_n$.

Define v_{-i} for $i = 0, 1, \dots$ by $v_{-i} := d_i u_i$, which implies that $v_0 = 0$, and set $v_1 = 1$. Then, since u_i is defined uniquely for $i \leq 0$ by the requirement that it satisfy (6) for $i \leq 0$ with the initial conditions that $u_0 = 0$ and $u_1 = 1$, to show (vii) it is enough to check that the sequence v_i satisfies (6) for $i \leq 0$, i.e. that

$$v_{-i+1} = \lambda v_{-i} - c_{-i} v_{-i-1}, \quad i = 0, 1, \dots$$

But $v_1 - \lambda v_0 + c_0 v_{-1} = 1 + c_0 d_1 u_1 = 0$, so the equation holds for $i = 0$, and, for $i \in \mathbb{N}$,

$$\begin{aligned} v_{-i+1} - \lambda v_{-i} + c_{-i} v_{-i-1} &= d_{i-1} u_{i-1} - \lambda d_i u_i + c_{i+1} d_{i+1} u_{i+1} \\ &= (d_{i-1} - c_i c_{i+1} d_{i+1}) u_{i-1} - \lambda (d_i - c_{i+1} d_{i+1}) u_i, \end{aligned}$$

since $u_{i+1} = \lambda u_i - c_i u_{i-1}$. Since $u_0 = 0$, the right hand side of this last equation is zero for $i \in \mathbb{N}$ provided that $d_i = c_{i+1} d_{i+1}$ for $i \in \mathbb{N}$. But this follows from the definitions of the sequences c and d . ■

Remark 2.4 The standard infinite discrete Sierpinski triangle (e.g. [24]) is the set $\tilde{S} \subset \mathbb{N}^2$ defined by $\tilde{S} := \cup_{n \in \mathbb{N}} \tilde{S}_n$, where $\tilde{S}_1 := \{(1, 1)\}$ and the sets \tilde{S}_n , $n = 2, 3, \dots$, are defined recursively by $\tilde{S}_{n+1} := 2\tilde{S}_n + \tilde{V}$, where $\tilde{V} := \{(0, 0), (-1, -1), (0, -1)\}$. One instance where \tilde{S} arises is as the pattern of odd coefficients in Pascal's triangle: for $i \in \mathbb{N}$ and $j = 1, \dots, i$ the coefficient of x^{j-1} in $(1+x)^{i-1}$ is odd iff $(i, j) \in \tilde{S}$, so that the discrete Sierpinski triangle is often referred to as Pascal's triangle modulo 2 (e.g. [13]). Proposition 2.1(vi) (cf. Remark 2.2) makes clear that the pattern $S \subset \mathbb{N}^2$ of the non-zero coefficients in table (7) is essentially that of the standard discrete Sierpinski triangle \tilde{S} ; indeed, the sets \tilde{S} and S are connected by a linear mapping: $(i, j) \in \tilde{S}$ iff $(2i - j, j) \in S$, for $i, j \in \mathbb{N}$. □

Remark 2.5 Note that the sequence c from Proposition 2.1 is not pseudo-ergodic since, by $c_{2i+1} = -c_{2i}$, the patterns “+ + +” and “- - -” can never occur as consecutive entries in the sequence c . \square

Based on Theorems 1.1 and 2.3 and the numerical results displayed in Figures 1.1 and 1.2, we make the following conjecture.

Conjecture. We conjecture that $\text{clos}(\sigma_\infty) = \text{clos}(\pi_\infty) = \text{spec } A^b$, and that $\text{spec } A^b$ is a simply connected set which is the closure of its interior and which has a fractal boundary.

Acknowledgements. We are grateful to Estelle Basor from the American Institute of Mathematics for drawing our attention to this beautiful operator class. Moreover, we would like to acknowledge: the financial support of a Leverhulme Fellowship and a visiting Fellowship of the Isaac Newton Institute Cambridge for the first author; the invitation of the second and third author to the MPA Workshop at the Isaac Newton Institute in July 2008; the financial support of a Higher Education Strategic Scholarship for Frontier Research from the Thai Ministry of Higher Education to the second author; and the Marie-Curie Grants MEIF-CT-2005-009758 and PERG02-GA-2007-224761 of the EU to the third author.

References

- [1] W. AMREIN, MANTOIU and R. PURICE: Propagation properties for Schrödinger operators affiliated with certain C^* -algebras, *Ann. H. Poincaré Int* **3** (2002), 1215–232.
- [2] A. BÖTTCHER and M. LINDNER: Pseudospectrum, *Scholarpedia* **3**(3):2680, 2008. <http://www.scholarpedia.org/article/Pseudospectrum>
- [3] A. BÖTTCHER and B. SILBERMANN: *Analysis of Toeplitz Operators*, 1st ed. Akademie-Verlag 1989 and Springer 1990; 2nd ed. Springer 2006.
- [4] R. CARMONA and J. LACROIX: *Spectral Theory of Random Schrödinger Operators*, Birkhäuser, Boston 1990.
- [5] S. N. CHANDLER-WILDE, R. CHONCHAIYA and M. LINDNER: Upper Bounds on the Spectra and Pseudospectra of Jacobi and Related Operators, *in preparation*.
- [6] S. N. CHANDLER-WILDE, R. CHONCHAIYA and M. LINDNER: On the Spectra and Pseudospectra of a Class of non-self-adjoint Random Matrices and Operators, *in preparation*.
- [7] S. N. CHANDLER-WILDE and M. LINDNER: Sufficiency of Favard’s condition for a class of band-dominated operators on the axis, *J. Funct. Anal.* **254** (2008), 1146–1159.
- [8] S. N. CHANDLER-WILDE and M. LINDNER: *Limit Operators, Collective Compactness, and the Spectral Theory of Infinite Matrices*, submitted for publication, and *Preprint 2008-7, TU Chemnitz* or *Preprint NI08017-HOP of INI Cambridge*.
- [9] G. M. CICUTA, M. Contedini and L. MOLINARI: Non-Hermitian tridiagonal random matrices and returns to the origin of a random walk, *J. Stat. Phys.* **98** (2000), 685–699.
- [10] E. B. DAVIES: Spectral properties of non-self-adjoint matrices and operators, *Proc. Royal Soc. A* **457** (2001), 191–206.
- [11] E. B. DAVIES: Spectral theory of pseudo-ergodic operators, *Commun. Math. Phys.* **216** (2001), 687–704.
- [12] E. B. DAVIES: *Linear Operators and their Spectra*, Cambridge University Press, 2007.

- [13] D. DOTY, X. GU, J. H. LUTZ, E. MAYORDOMO. and P. MOSER: Zeta dimension, in *Mathematical Foundations of Computer Science 2005*, Springer, 2005, pp. 283–294.
- [14] K. J. FALCONER: *Fractal Geometry: Mathematical Foundations & Applications*, John Wiley & Sons, 1990.
- [15] J. FEINBERG and A. ZEE: Non-Hermitian Localization and De-Localization, *Phys. Rev. E* **59** (1999), 6433–6443.
- [16] J. FEINBERG and A. ZEE: Spectral Curves of Non-Hermitian Hamiltonians, *Nucl. Phys. B* **552** (1999), 599–623.
- [17] V. GEORGESCU and S. GOLENIA: Isometries, Fock spaces and spectral analysis of Schrödinger operators on trees, *Journal of Functional Analysis* **227** (2005), 389–429.
- [18] V. GEORGESCU and A. IFTIMOVICI: C*-Algebras of Energy Observables: I. General Theory and Bumps Algebras, *Preprint 00-521* at http://www.ma.utexas.edu/mp_arc/, December 2000.
- [19] V. GEORGESCU and A. IFTIMOVICI: Crossed products of C*-algebras and spectral analysis of quantum Hamiltonians, *Comm. Math. Phys.* **228** (2002), 519–560.
- [20] V. GEORGESCU and A. IFTIMOVICI: Localization at infinity and essential spectrum of quantum Hamiltonians, [arXiv:math-ph/0506051v1](https://arxiv.org/abs/math-ph/0506051v1), June 2005.
- [21] I. GOLDSHEID and B. KHORUZHENKO: Eigenvalue curves of asymmetric tridiagonal random matrices, *Electronic Journal of Probability* **5** (2000), 1–28.
- [22] D.E. HOLZ, H. ORLAND and A. ZEE: On the remarkable spectrum of a non-Hermitian random matrix model, *Journal of Physics A: Mathematical and General* **36** (2003), 3385–3400.
- [23] V. G. KURBATOV: *Functional Differential Operators and Equations*, Kluwer Academic Publishers, Dordrecht, Boston, London 1999.
- [24] J. I. LATHROPA, J. H. LUTZ, and S. M. SUMMERS: Strict self-assembly of discrete Sierpinski triangles, *Theor. Computer Sci.* **410** (2009) 384–405.
- [25] Y. LAST and B. SIMON: Eigenfunctions, transfer matrices, and absolutely continuous spectrum of one-dimensional Schrödinger operators, *Invent. Math.* **135** (1999), 329–367.
- [26] Y. LAST and B. SIMON: The essential spectrum of Schrödinger, Jacobi and CMV operators, *J. Anal. Math.* **98** (2006) 183–220.
- [27] M. LINDNER: *Infinite Matrices and their Finite Sections: An Introduction to the Limit Operator Method*, Frontiers in Mathematics, Birkhäuser 2006.
- [28] M. LINDNER: Fredholmness and index of operators in the Wiener algebra are independent of the underlying space, *Operators and Matrices* **2** (2008), 297–306.
- [29] M. LINDNER: A note on the spectrum of bi-infinite bi-diagonal random matrices, *TU Chemnitz Preprint* 12, 2008.
- [30] M. LINDNER: Fredholm Theory and Stable Approximation of Band Operators and Generalisations, *Habilitation thesis*, TU Chemnitz, 2009.
- [31] M. MANTOIU: C*-algebras, dynamical systems at infinity and the essential spectrum of generalized Schrödinger operators, *J. Reine Angew. Math.* **550** (2002), 211–229.
- [32] L. A. PASTUR and A. L. FIGOTIN: *Spectra of Random and Almost-Periodic Operators*, Springer, Berlin 1992.

- [33] V. S. RABINOVICH and S. ROCH: The essential spectrum of Schrödinger operators on lattices, *J. Phys. A: Math. Gen.* **39** (2006) 8377–9394.
- [34] V. S. RABINOVICH, S. ROCH and B. SILBERMANN: Fredholm Theory and Finite Section Method for Band-dominated operators, *Integral Equations Operator Theory* **30** (1998), no. 4, 452–495.
- [35] V. S. RABINOVICH, S. ROCH and B. SILBERMANN: *Limit Operators and Their Applications in Operator Theory*, Birkhäuser 2004.
- [36] C. REMLING: The absolutely continuous spectrum of Jacobi matrices, [arXiv:0706.1101v1](https://arxiv.org/abs/0706.1101v1), June 2007.
- [37] C. REMLING: The Absolutely Continuous Spectrum of One-dimensional Schrödinger Operators, *Math. Phys., Anal. and Geom.* **10** (2007), 359–373.
- [38] L. N. TREFETHEN and M. EMBREE: *Spectra and pseudospectra: The behavior of nonnormal matrices and operators*, Princeton University Press, Princeton, NJ, 2005.

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