

Self-Affine Tiling Via Substitution Dynamical Systems and Rauzy Fractals

Víctor F. Sirvent*
Departamento de Matemáticas
Universidad Simón Bolívar
Caracas 1086-A, Venezuela

Yang Wang†
School of Mathematics
Georgia Institute of Technology
Atlanta, GA 30332, USA

November 19, 2001

Abstract

In this paper we show that a class of sets known as the Rauzy fractals, which are constructed via substitution dynamical systems, give rise to self-affine multi-tiles and self-affine tilings. This provides an efficient and unconventional way for constructing aperiodic self-affine tilings. Our result also leads to a proof that a Rauzy fractal \mathfrak{R} associated with a primitive and unimodular Pisot substitution has nonempty interior.

Key Words: unimodular Pisot substitution, Rauzy fractal, self-affine multi-tile, self-affine tiling, iterated function systems.

AMS subject classification (1991): 28A80, 52C22, 58F08, 11B85.

1 Introduction

Let A be an expanding matrix in $M_d(\mathbb{R})$, that is, one with all eigenvalues $|\lambda| > 1$. Let \mathcal{D}_{ij} where $1 \leq i, j \leq J$ be finite (possibly empty) subsets of vectors in \mathbb{R}^d . It is known (see [16]) that there exist unique nonempty compact sets X_1, \dots, X_J such that

$$A(X_i) = \bigcup_{j=1}^J (X_j + \mathcal{D}_{ij}), \quad i = 1, \dots, J, \quad (1.1)$$

provided that the *subdivision matrix* $S = [s_{ij}]$ where $s_{ij} := |\mathcal{D}_{ij}|$ is primitive. The J -tuple (X_1, \dots, X_J) is called the attractor of the graph-directed iterated function system (IFS) (1.1).

An interesting class of graph-directed IFS consists of those whose attractors are tiles of \mathbb{R}^d . We say that (X_1, \dots, X_J) is a *self-affine multi-tile* if each X_i has nonempty interior

*Research supported in part by Conicit (Venezuela). e-mail: vsirvent@usb.ve

†Research supported in part by NSF grant DMS-97-06793. e-mail: wang@math.gatech.edu

and the unions on the right side of (1.1) are all measure-wise disjoint. Self-affine multi-tiles arise in many applications, include the construction of orthonormal multi-wavelet bases, self-replicating tilings and quasicrystals. They form an important class of tiles in the theory of tiling. For example, the Penrose aperiodic tiles can be viewed as a self-affine multi-tile. By iterating the equation (1.1) repeatedly we may obtain a *self-affine* tiling, or *self-replicating* tiling. Such inflation technique remains as the most effective way for generating aperiodic and “exotic” tilings. For more on self-affine multi-tiles and tilings, see [6], [8], [12], and the references therein.

Self-affine multi-tiles and self-affine tilings are the easiest to construct when the expanding matrix A is an integer matrix, or is similar to an integer matrix. The studies in some of the recent papers (e.g. [6], [8]) are mostly confined to such settings. These multi-tiles typically – although not always – yield periodic self-affine tilings. However, the most interesting multi-tiles such as some of the Penrose tiles that yield aperiodic self-affine tilings do not use integer matrices as the expansion matrix. Constructions of self-affine multi-tiles and self-affine tilings systematically using non-integer matrices remain difficult in general.

Our main objective in this paper is to introduce a method for constructing interesting self-affine multi-tiles and self-affine tilings, in which the expansion matrix A is not an integral matrix. The self-affine multi-tiles and tilings are obtained through substitution dynamical systems, via a peculiar class of sets called the *Rauzy fractals*. We first give a brief introduction on substitution dynamical systems and Rauzy fractals below.

A *substitution* on a finite alphabet $\mathcal{A} = \{1, \dots, n\}$ is a map Π from \mathcal{A} to $\mathcal{A}^* = \bigcup_{i \geq 0} \mathcal{A}^i$, where \mathcal{A}^i denotes the set of words of length i in \mathcal{A} , with \mathcal{A}^0 containing only the empty word \emptyset . This map extends to a map on \mathcal{A}^* into itself by juxtaposition $\Pi(\emptyset) = \emptyset$ and $\Pi(UV) = \Pi(U)\Pi(V)$ for all $U, V \in \mathcal{A}^*$. Let $\mathcal{A}^{\mathbb{N}}$ denote the set of one sided infinite sequences in the alphabet \mathcal{A} :

$$\mathcal{A}^{\mathbb{N}} := \left\{ a_1 a_2 a_3 \cdots \mid a_j \in \mathcal{A} \right\}.$$

Then Π extends to a map on $\mathcal{A}^{\mathbb{N}}$ into itself in the obvious way. An important object associated to a substitution is its *incidence matrix*. For any $U \in \mathcal{A}^*$ let $|U|_j$ denote the number of occurrences of the symbol j in the word U . The incidence matrix $M = [m_{ij}]$ is then defined by $m_{ij} = |\Pi(i)|_j$ for $1 \leq i, j \leq n$. Throughout this paper we shall assume that the substitution Π is *primitive*, namely $M^k > 0$ for some $k \geq 1$.

We call $\mathbf{U} \in \mathcal{A}^{\mathbb{N}}$ a *fixed point* of Π if $\Pi(\mathbf{U}) = \mathbf{U}$. Associated to a fixed point \mathbf{U} of the substitution is a symbolic dynamical system $(\Omega_{\mathbf{U}}, \sigma)$ where σ is the shift map on $\mathcal{A}^{\mathbb{N}}$ given by $\sigma(a_1 a_2 \cdots) = a_2 a_3 \cdots$ and $\Omega_{\mathbf{U}}$ is the closure of $\{\sigma^m(\mathbf{U}) : m \geq 0\}$ in $\mathcal{A}^{\mathbb{N}}$. This symbolic dynamical system has been studied extensively, see Queffélec [20]. It is straightforward to show that if the substitution is primitive then the system $(\Omega_{\mathbf{U}}, \sigma)$ is minimal and uniquely ergodic.

An important question is whether and how the symbolic dynamical system $(\Omega_{\mathbf{U}}, \sigma)$ is realizable geometrically. We say that a dynamical system (X, f) is *semiconjugate* to another dynamical system (Y, g) if there exists a continuous surjective map $\phi : X \rightarrow Y$ such that $\phi \circ f = g \circ \phi$. By *geometrically realizable* we mean there exists a dynamical system (X, f) defined on a geometrical structure, e.g. a differentiable manifold, for some continuous map

f on X , such that $(\Omega_{\mathbf{U}}, \sigma)$ is semiconjugate to (X, f) . One of the main motivations of this question is the study of the spectral properties of the symbolic system. One way to do this is to show that symbolic system is measurably conjugate or semiconjugate to the geometrical system. In particular a way to show that a substitution dynamical systems has discrete spectrum is to find a isomorphism to rotation on a compact group [cf. [20, 21, 32]]. It has been conjectured that every primitive and unimodular Pisot substitution dynamical system is measurably isomprhic to a toral translation.

Rauzy approached this conjecture via geometrical realization of the symbolic system. In [23] he studied the tribonacci substitution, i.e. $1 \rightarrow 12, 2 \rightarrow 13, 3 \rightarrow 1$, and he showed that the associated symbolic dynamical system can be realized geometrically as (\mathbb{T}^2, f) where f is an irrational translation on the 2-torus \mathbb{T}^2 . This result generalizes also to the family of substitutions

$$1 \rightarrow 12, 2 \rightarrow 13, \dots, (n-1) \rightarrow 1n, n \rightarrow 1. \quad (1.2)$$

The symbolic dynamical system $(\Omega_{\mathbf{U}}, \sigma)$ associated to the unique fixed point for each n is geometrically realizable as (\mathbb{T}^{n-1}, f_n) for some irrational translation f_n on \mathbb{T}^{n-1} .

Key to Rauzy's results is the construction of a set known as a *Rauzy fractal* associated to the fixed point \mathbf{U} of a primitive substitution. In [23] the set $\Omega_{\mathbf{U}}$ is mapped to \mathbb{C} via a *valuation*, which is a map $E : \mathcal{A}^* \rightarrow \mathbb{C}$ having the properties that $E(UV) = E(U) + E(V)$ and $E(\Pi(U)) = \omega E(U)$ for all $U, V \in \mathcal{A}^*$ and some fixed constant ω . It is shown in Holton and Zamboni [9] that in a valuation the constant ω must be an eigenvalue of the incidence matrix M , and there exists an ω -eigenvector $\mathbf{v} = [v_1, \dots, v_n]^T$ such that

$$E(U) = \sum_{i=1}^n |U|_i v_i, \text{ for all } U \in \mathcal{A}^*. \quad (1.3)$$

We call the valuation defined above the *valuation corresponding to \mathbf{v}* . Suppose that

$$\omega_1, \bar{\omega}_1, \dots, \omega_p, \bar{\omega}_p, \omega_{p+1}, \dots, \omega_r \quad (1.4)$$

are all the eigenvalues of M inside the unit disk, where $\omega_1, \bar{\omega}_1, \dots, \omega_p, \bar{\omega}_p$ are nonreal complex and $\omega_{p+1}, \dots, \omega_r$ are real. Let \mathbf{v}_j be an ω_j -eigenvector of M and E_j be the valuation corresponding to \mathbf{v}_j . For $U \in \mathcal{A}^*$ define $\Delta(U) = [E_1(U), \dots, E_r(U)]^T$. Note that $\Delta(U)$ is a vector in $\mathbb{C}^p \times \mathbb{R}^{r-p}$, which we identify with \mathbb{R}^{p+r} . The valuation done by Rauzy in [23] in the tribonacci substitution is shown in Example 2.1.

Definition 1.1 *We call the closure of the set $\{\Delta([\mathbf{U}]_m) : m \geq 0\}$ in $\mathbb{C}^p \times \mathbb{R}^{r-p}$ (identified with \mathbb{R}^{p+r}) a *Rauzy fractal*, where $[\mathbf{U}]_m$ is the word formed by the first m symbols of the fixed point \mathbf{U} .*

It is known that a Rauzy fractal is bounded ([23, 9]). The geometric and dynamical properties of Rauzy fractals have been studied in a number of papers, among others see [1, 9, 23, 27, 28, 30]. For example, Holton and Zamboni [9] studied the Hausdorff dimensions of various sets related to Rauzy fractals. They also observed that a Rauzy fractal can be expressed as the attractor of some graph directed iterated function system (IFS). Solomyak

[30, 32] showed that certain family of primitive and unimodular Pisot substitutions (defined below) has pure discrete spectrum via geometrical realizations as irrational translations on tori. Arnoux and Ito [1] showed that for certain primitive and unimodular Pisot substitutions on a alphabet of k letters can be realized geometrically as an exchange of pieces by translation on the plane \mathbb{R}^{k-1} and as irrational translations on \mathbb{T}^{k-1} . The geometry of boundary of the Rauzy fractal for the tribonacci substitution has been studied in [29, 17].

We shall study Rauzy fractals associated to fixed points of primitive and *unimodular Pisot* substitutions. A substitution Π in $n \geq 2$ symbols is unimodular Pisot if its incidence matrix M satisfies (i) $|\det(M)| = 1$ and (ii) the Perron-Frobenius eigenvalue λ of M is a Pisot number, and the characteristic polynomial of M is the minimal polynomial of λ , i.e. it is irreducible over \mathbb{Q} . A Pisot number is an algebraic integer greater than 1, such that all its Galois conjugates have modulus less than 1. Most of the studies on Rauzy fractals assume the substitutions are primitive and unimodular Pisot because only such substitutions allow geometric realizations.

In this paper we prove several general properties concerning self-affine multi-tiles in §3. These results are themselves rather fundamental for the study of self-affine multi-tiles and tilings. We then use these results to prove in §4 a main theorem of ours, that the so-called *natural decomposition* of a Rauzy fractal \mathfrak{R} (defined later) gives a self-affine multi-tile. The expansion matrix for the self-affine multi-tile is not an integer matrix; in fact it is not even similar to an integer matrix. As a corollary we prove that every set in the natural decomposition of \mathfrak{R} has nonempty interior and is in fact the closure of its interior. Our method yields a simple new proof of a result, due to Arnoux and Ito [1], concerning the disjointness of the natural decomposition of \mathfrak{R} .

We should point out that self-similar tilings using non-integral expansions are not new. In an unpublished work Thurston [34] outlined a construction of self-similar tilings for a complex Pisot number β . This construction, which was studied further in Kenyon [11, 12], Praggastis [19] and Petronio [18], employs base- β expansions (called β -expansions) $\sum_{j \in \mathbb{Z}} d_j \beta^j$ with d_j belonging to a suitably chosen set $\mathcal{D} \subset \mathbb{Q}(\beta)$ called the “digit set.” The expansions are not unique in general. However, it is possible to make the expansions unique by disallowing some subsequences. Once this is done, the remaining β -expansions form a partition of the plane that is a self-similar tiling using the expansion β . Although coming from a completely different angle, the Rauzy fractal induced self-affine tilings turn out to be related to Thurston’s framework. This is evident in Rauzy’s work on the tribonacci substitution Rauzy fractal. The general Rauzy fractals studied here provide a concrete and very general construction of Thurston-like self-affine tilings. Moreover, these Rauzy fractals allow the expanding matrices to be nonsimilitudes. We also mention that unlike in much previously mentioned work, we prove the tiling property of Rauzy fractals by proving first they have positive Lebesgue measure and then establishing structural results on the expansions, rather than the other way around.

The fact that \mathfrak{R} has positive Lebesgue measure had been conjectured and is a key part for the geometric realization of substitution dynamical systems. This fact has recently also been proved independently by Canterini and Siegel [3], following from a stronger result of theirs concerning the geometric realization of substitutions. Their methods are rather

different from ours, and they are motivated by geometric realization of substitutions rather than self-affine tilings. In a later paper [4], Canterini and Siegel also gave an alternative proof that every set in the natural decomposition of \mathfrak{R} has nonempty interior using a very different method.

Acknowledgments: The first author would like to thank the School of Mathematics of the Georgia Institute of Technology for its hospitality. This article was completed during a visit by the first author to this institution.

2 Preliminary Results

The objective of this section is to prove that a Rauzy fractal associated to a fixed point of a primitive and unimodular Pisot substitution has positive Lebesgue measure. This fact is needed to prove our main results.

Throughout the rest of the paper, unless otherwise stated, \mathcal{A} denotes the alphabet $\mathcal{A} = \{1, 2, \dots, n\}$ and Π is a primitive and unimodular Pisot substitution on \mathcal{A} , with incidence matrix $M = [m_{ij}]$. We use \mathbf{U} to denote a fixed point of Π and $[\mathbf{U}]_k$ to denote the word formed by the first k symbols of \mathbf{U} . The Perron-Frobenius eigenvalue of M is λ , and all the other eigenvalues of M are $\omega_1, \bar{\omega}_1, \dots, \omega_p, \bar{\omega}_p, \omega_{p+1}, \dots, \omega_r$, where $\omega_1, \dots, \omega_p$ are nonreal complex and $\omega_{p+1}, \dots, \omega_r$ are real. Of course, the unimodular Pisot assumption implies that $0 < |\omega_j| < 1$. The map E_j is a valuation corresponding to some ω_j -eigenvector \mathbf{v}_j , as defined in (1.3), and $\Delta = [E_1, \dots, E_r]^T$.

Observe that each \mathbf{v}_j is unique up to scaling. Therefore the Rauzy fractal associated to the substitution Π on \mathcal{A} is actually *unique* up to an affine transformation. Also, by elementary linear algebra the fact that the characteristic polynomial is irreducible over \mathbb{Q} implies that there exist polynomials $g_i(x) \in \mathbb{Z}[x]$ of degrees less than n for $1 \leq i \leq n$ such that

$$\mathbf{v}_j = [g_1(\omega_j), \dots, g_n(\omega_j)]^T c_j, \quad (2.1)$$

where $c_j \neq 0$ and $c_j \in \mathbb{C}$ for $j \leq p$ and $c_j \in \mathbb{R}$ for $j > p$.

Lemma 2.1 *Let E be the valuation corresponding to some ω -eigenvector \mathbf{v} . Then $E(UV) = E(U) + E(V)$ and $E(\Pi(U)) = \omega E(U)$ for all $U, V \in \mathcal{A}^*$.*

Proof. This is shown in [9], and we include a proof for self-containment. The fact $E(UV) = E(U) + E(V)$ follows from the definition. Also by definition,

$$E(\Pi(i)) = \sum_{j=1}^n m_{ij} E(j) = \sum_{j=1}^n m_{ij} v_j = \omega v_i = \omega E(i),$$

where $\mathbf{v} = [v_1, \dots, v_n]^T$. By juxtaposition we see that $E(\Pi(U)) = \omega E(U)$ for all $U \in \mathcal{A}^*$. ■

Lemma 2.2 $\Delta([\mathbf{U}]_m) \neq \Delta([\mathbf{U}]_k)$ for $m \neq k$.

Proof. We prove the stronger statement that $E_i([\mathbf{U}]_m) \neq E_i([\mathbf{U}]_k)$ for all $m \neq k$. Suppose that this is not true. Then $E_i([\mathbf{U}]_m) = E_i([\mathbf{U}]_k)$ for some $m \neq k$. Without loss of generality let $k > m$. Then by definition and (2.1), $\sum_{j=1}^n |V|_j g_j(\omega_i) = 0$, where V is the word formed using the $(m+1)$ -th through k -th symbols of \mathbf{U} . But $g_j(x) \in \mathbb{Z}[x]$ and λ is a Galois conjugate of ω_i , so we must have $\sum_{j=1}^n |V|_j g_j(\lambda) = 0$. However, since λ is the Perron-Frobenius eigenvalue of M and M is primitive, all $g_j(\lambda)$ are positive or negative at the same time. This is impossible. So $E_i([\mathbf{U}]_m) \neq E_i([\mathbf{U}]_k)$ for all $m \neq k$, proving the lemma. \blacksquare

For each polynomial $f(x)$ we let $\boldsymbol{\omega}_f = [f(\omega_1^{-1}), \dots, f(\omega_r^{-1})]^T$.

Lemma 2.3 *Let D be a finite subset of \mathbb{Z} and let $D[x]$ denote*

$$D[x] = \left\{ f(x) = a_0 + \dots + a_m x^m \mid a_j \in D, m \geq 0 \right\}.$$

Then there exists an $\varepsilon_0 > 0$ depending only on D , such that for all $f, g \in D[x]$ either $\boldsymbol{\omega}_f = \boldsymbol{\omega}_g$ or $\|\boldsymbol{\omega}_f - \boldsymbol{\omega}_g\| \geq \varepsilon_0$.

Proof. Note that the unimodular Pisot assumption implies that $1/\lambda$ is an algebraic integer and its Galois conjugates are precisely

$$\omega_1^{-1}, \bar{\omega}_1^{-1}, \dots, \omega_p^{-1}, \bar{\omega}_p^{-1}, \omega_{p+1}^{-1}, \dots, \omega_r^{-1}.$$

So for each $f(x)$ in $\mathbb{Z}[x]$ the Galois conjugates of $f(\lambda)$ are $f(\lambda^{-1}), f(\omega_1^{-1}), f(\bar{\omega}_1^{-1}), \dots, f(\omega_r^{-1})$. Therefore

$$L(f) := f(\lambda^{-1}) + f(\omega_1^{-1}) + f(\bar{\omega}_1^{-1}) + \dots + f(\omega_r^{-1}) \in \mathbb{Z}. \quad (2.2)$$

In particular since $f_k(x) = x^k f(x) \in \mathbb{Z}[x]$ we have $L(f_k) := L_k \in \mathbb{Z}$ for all $k \geq 0$.

Using the Vandermonde matrix it is easy to prove that for any k , at least one of $L_k, L_{k+1}, \dots, L_{k+n-1}$ is not zero, unless $f(\lambda^{-1}) = f(\omega_i^{-1}) = 0$ for all i .

The finiteness of D implies $|f(\lambda^{-1})| \leq c_0$ for some c_0 depending only on D . Now assume that the lemma is false. Then we can find f, g in $D[x]$ with $\boldsymbol{\omega}_f \neq \boldsymbol{\omega}_g$ such that $\|\boldsymbol{\omega}_f - \boldsymbol{\omega}_g\|$ can be made arbitrarily small. Since $h(x) = f(x) - g(x)$ satisfies $|h(\lambda^{-1})| \leq 2c_0$, $|\lambda^{-k} h(\lambda^{-1})|$ is sufficiently small for sufficiently large k . We derive a contradiction below.

Fix $k > 0$ such that $2\lambda^{-k} c_0 < \frac{1}{n}$. Then choose $f(x), g(x) \in D[x]$ such that $h(x) = f(x) - g(x)$ has the property that $\boldsymbol{\omega}_h \neq 0$ and $\|\boldsymbol{\omega}_h\|$ is so small that for $h_j(x) := x^j h(x)$ we have

$$\|\boldsymbol{\omega}_{h_{j+k}}\| \leq \max_{1 \leq i \leq r} |\omega_i|^{-j-k} \|\boldsymbol{\omega}_h\| < \frac{1}{n}$$

for $0 \leq j \leq n-1$. Since also

$$|h_{j+k}(\lambda^{-1})| = \lambda^{-j-k} |h(\lambda^{-1})| \leq 2\lambda^{-j-k} c_0 < \frac{1}{n}$$

we have that $|L(h_{j+k})| < 1$ for $0 \leq j \leq n-1$. But all $L(h_{j+k})$ are integers, so all of them must be 0. This contradicts the result that one of them is nonzero, proving the lemma. \blacksquare

Corollary 2.4 *Let S be a finite subset of $\mathbb{Z}[x]$. If in Lemma 2.3 $D[x]$ is replaced by*

$$S[x] = \left\{ f(x) = a_0(x) + a_1(x)x + \cdots + a_m(x)x^m \mid a_i(x) \in S, m \geq 0 \right\},$$

then the same conclusion still holds.

Proof. Because S is finite, there exists a finite $D \subset \mathbb{Z}$ such that $S[x] \subseteq D[x]$. So the conclusion of Lemma 2.3 still holds. \blacksquare

We shall need the following theorem of Rauzy [24] to prove our results:

Theorem 2.5 (Rauzy) *There exists a finite subset \mathcal{P} of \mathcal{A}^* with $\emptyset \in \mathcal{P}$ and a subset \mathcal{S} of \mathcal{P}^* , the set of all finite sequences in \mathcal{P} , with the following properties:*

- (a) *All sequences $(W_k, W_{k-1}, \dots, W_0) \in \mathcal{S}$ satisfy $W_k \neq \emptyset$.*
- (b) *For any $m \geq 1$ there exists a unique sequence of words $(W_k, W_{k-1}, \dots, W_0) \in \mathcal{S}$ such that*

$$[\mathbf{U}]_m = \Pi^k(W_k)\Pi^{k-1}(W_{k-1}) \cdots \Pi(W_1)W_0. \quad (2.3)$$

- (c) *For any sequence of words $(W_k, W_{k-1}, \dots, W_0) \in \mathcal{S}$ there exists an $m \geq 1$ such that $[\mathbf{U}]_m$ is given by (2.3).*

Proof. See the theorem in Rauzy [24], First part, Section 6. \blacksquare

The above theorem of Rauzy's is proved by representing $[\mathbf{U}]_m$ as a path in certain prefix automaton. The set \mathcal{P} is the set of prefixes for the automaton and \mathcal{S} is the set of all allowable paths generated by the prefix automaton. Using this representation many elegant results can be derived, see [24] for more details.

Lemma 2.6 *There exists a finite subset S of $\mathbb{Z}[x]$ such that*

$$\{\Delta([\mathbf{U}]_m) \mid m \geq 1\} \subseteq \left\{ \sum_{j=0}^k \omega_{p_j} B^j \mathbf{v}_0 \mid p_j(x) \in S, k \geq 0 \right\} \quad (2.4)$$

where B is the matrix $B := \text{diag}(\omega_1, \omega_2, \dots, \omega_r)$ and \mathbf{v}_0 is a fixed vector in $\mathbb{C}^p \times \mathbb{R}^{r-p}$.

Proof. By Theorem 2.5, the word $[\mathbf{U}]_m$ can be expressed as $\Pi^k(W_k)\Pi^{k-1}(W_{k-1}) \cdots W_0$, where $W_j \in \mathcal{P}$ for some finite $\mathcal{P} \in \mathcal{A}^*$ and $W_k \neq \emptyset$. Observe that for each $W \in \mathcal{P}$, $E_i(W) = q(\omega_i)c_i$ for some $q(x) \in \mathbb{Z}[x]$ and constant c_i . Since \mathcal{P} is finite we may choose a sufficiently large fixed N so that $q(x) = x^N p(x^{-1})$ for some $p(x) \in \mathbb{Z}[x]$. So $E_i(W) = p(\omega_i^{-1})\omega_i^N c_i$. It follows that

$$E_i([\mathbf{U}]_m) = \sum_{j=0}^k \omega_i^j E_i(W_j) = \sum_{j=0}^k \omega_i^j p(\omega_i^{-1})\omega_i^N c_i.$$

The lemma is proved by setting $\mathbf{v}_0 = [\omega_1^N c_1, \dots, \omega_r^N c_r]^T$. \blacksquare

Lemma 2.7 *Let N be a positive integer and define*

$$R_N = \left\{ \Delta(U) \mid U = \Pi^k(W_k) \cdots \Pi(W_1)W_0, (W_k, \dots, W_0) \in \mathcal{S} \text{ and } k \leq N \right\}$$

where \mathcal{S} is defined in Theorem 2.5. Then R_N is a subset of $\{\Delta([\mathbf{U}]_m) : m \geq 0\}$, and there exist $C_1, C_2 > 0$ independent of N such that the cardinality of R_N satisfies

$$C_1 \lambda^N \leq |R_N| \leq C_2 \lambda^N.$$

Proof. $R_N \subseteq \{\Delta([\mathbf{U}]_m) : m \geq 0\}$ follows from Theorem 2.5.

For each $U \in \mathcal{A}^*$ the length of $\Pi^l(U)$ is $\sum_{i,j=1}^n m_{ij}^{(l)} |U|_j$, where $m_{ij}^{(l)}$ are the entries of the matrix M^l . So the length is bounded by $C_0 \lambda^l \max(|U|_j)$ for some constant C_0 independent of U and l . The inequality $|R_N| \leq C_2 \lambda^N$ is now obvious, because \mathcal{P} is finite. To prove $|R_N| \geq C_1 \lambda^N$, consider

$$\sum_{i=1}^n |\Pi^k(W_k) \cdots \Pi(W_1)W_0|_i \geq \sum_{i=1}^n |\Pi^k(W_k)|_i \geq C_3 \lambda^k$$

for some $C_3 > 0$. Therefore, for all m such that $[\mathbf{U}]_m$ is not representable as $\Pi^k(W_k) \cdots W_0$ with $k \leq N$ we must have $\sum_{i=1}^n |U_m|_i = m \geq C_3 \lambda^{N+1}$. Hence $R_N \supseteq \{\Delta(U_m) \mid m < C_3 \lambda^{N+1}\}$. Since all $\Delta([\mathbf{U}]_m)$ are distinct by Lemma 2.2, we have

$$|R_N| \geq C_3 \lambda^{N+1} = (C_3 \lambda) \lambda^N = C_1 \lambda^N. \quad \blacksquare$$

Proposition 2.8 *The Rauzy fractal \mathfrak{R} has positive Lebesgue measure.*

Proof. By Lemma 2.6 and Corollary 2.4 the set $B^{-N}(R_N)$ has the ε_0 -separation property for some $\varepsilon_0 > 0$. Let $\delta = \varepsilon_0/2$ and $B_\delta(y)$ be the ball of radius δ centered at y in $\mathbb{C}^p \times \mathbb{R}^{r-p}$ (which we identify with \mathbb{R}^{n-1}). Then

$$S_N = \bigcup_{y \in B^{-N}(R_N)} B_\delta(y)$$

is a disjoint union of balls. So $\nu(S_N) = |R_N| \text{vol}(B_\delta(0))$, where ν denotes the Lebesgue measure. Note that for any set K ,

$$\nu(B(K)) = |\omega_1|^2 \cdots |\omega_p|^2 |\omega_{p+1}| \cdots |\omega_r| \nu(K) = \lambda^{-1} \nu(K). \quad (2.5)$$

(Note that the first p coordinates are complex.) Hence $\nu(B^N(S_N)) = \lambda^{-N} |R_N| \text{vol}(B_\delta(0))$. It follows from Lemma 2.7 that $\nu(B^N(S_N)) \geq C_1 \text{vol}(B_\delta(0)) > 0$. On the other hand the limit of $B^N(S_N)$, when N goes to infinity, is \mathfrak{R} in the Hausdorff metric. This implies $\nu(\mathfrak{R}) \geq \liminf_{N \rightarrow \infty} \nu(B^N(S_N)) > 0$. \blacksquare

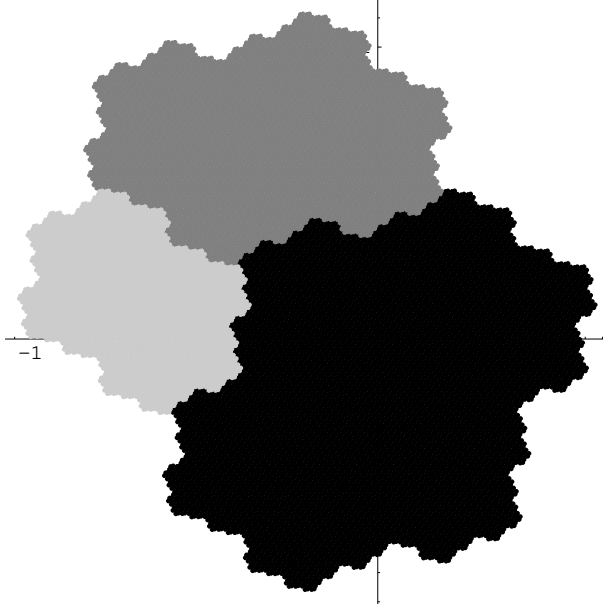


Figure 1: The Rauzy fractal of the substitution $1 \rightarrow 12, 2 \rightarrow 13, 3 \rightarrow 1$.

Example 2.1 We consider the substitution $1 \rightarrow 12, 2 \rightarrow 13, 3 \rightarrow 1$. A simple induction argument shows that it satisfies the relation

$$\Pi^{l+3}(1) = \Pi^{l+2}(1)\Pi^{l+1}(1)\Pi^l(1) \quad (2.6)$$

for all $l \geq 0$. It is shown (see [24]), using this fact, that $[\mathbf{U}]_m = \Pi^k(W_k) \cdots \Pi(W_1)W_0$, where W_i are either \emptyset or 1 and k depends on m but having no three consecutive W_i 's equal to 1. So the set \mathcal{S} in Theorem 2.5 is the set of infinite one-sided sequences in the symbols $\mathcal{P} = \{\emptyset, 1\}$, such that there are no three consecutive 1's. Therefore $\Delta([\mathbf{U}]_m) = \sum_{i=0}^k \omega^i \Delta(W_i)$ where ω is one of the two conjugate eigenvalues inside the unit circle, with

$$\Delta(W_i) = \begin{cases} 0 & \text{if } W_i = \emptyset, \\ 1 & \text{if } W_i = 1. \end{cases}$$

Hence

$$\mathfrak{R} = \left\{ \sum_{i \geq 0} a_i \omega^i \mid a_i \in \{\emptyset, 1\} \text{ and } a_i a_{i+1} a_{i+2} = 0 \text{ for all } i. \right\}.$$

This set is shown in Figure 1 (the different shades correspond to the decomposition of \mathfrak{R} , discussed in the next section).

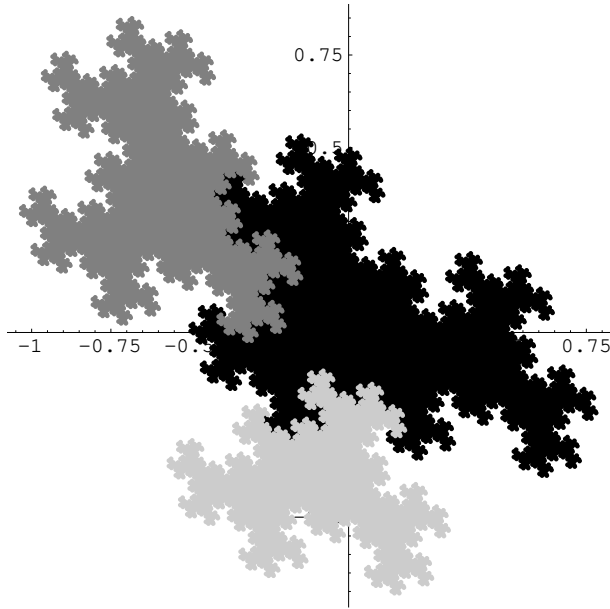


Figure 2: The Rauzy fractal of the substitution $1 \rightarrow 12, 2 \rightarrow 3, 3 \rightarrow 1$.

Example 2.2 Let the substitution be $1 \rightarrow 12, 2 \rightarrow 3, 3 \rightarrow 1$. Let ω be one of the two complex conjugate eigenvalues of the incidence matrix of this substitution. It can be proved, using the techniques described in [24], that

$$\mathfrak{R} = \left\{ \sum_{i \geq 0} a_i \omega^i \mid a_i \in \{0, 1\} \text{ and if } a_i = 1 \text{ for } i \geq 2 \text{ then } a_{i-1} = a_{i-2} = 0. \right\}.$$

This set is shown in Figure 2.

3 Graph-Directed IFS and Self-Affine Multi-Tiles

In this section we establish results concerning self-affine multi-tiles. In particular we prove a theorem regarding nonempty interior of the attractor of a graph directed IFS in a more general setting. Let A be an expanding $d \times d$ matrix, i.e. all its eigenvalues are outside the unit disk. Consider the nonempty compact subsets X_1, \dots, X_J of \mathbb{R}^d such that (X_1, \dots, X_J) is the attractor of the graph directed IFS

$$X_i = \bigcup_{j=1}^J A^{-1}(X_j + \mathcal{D}_{ij}), \quad i = 1, \dots, J, \quad (3.1)$$

where each \mathcal{D}_{ij} is a finite (possibly empty) subset of \mathbb{R}^d . For our study it is more convenient to write (3.1) in the form of

$$A(X_i) = \bigcup_{j=1}^J (X_j + \mathcal{D}_{ij}), \quad i = 1, \dots, J. \quad (3.2)$$

Iterating (3.2) yields

$$A^m(X_i) = \bigcup_{j=1}^J (X_j + \mathcal{D}_{ij}^m), \quad i = 1, \dots, J, \quad (3.3)$$

where one easily check that

$$\mathcal{D}_{ij}^m = \bigcup_{k_1, \dots, k_m=1}^J (A^{m-1}\mathcal{D}_{ik_m} + A^{m-2}\mathcal{D}_{k_mk_{m-1}} + \dots + \mathcal{D}_{k_1j}). \quad (3.4)$$

We say that the graph directed IFS (3.1) is *strongly connected* if its *subdivision matrix* $S = [s_{ij}]$ for $s_{ij} = |\mathcal{D}_{ij}|$ is primitive.

Theorem 3.1 *Let (X_1, \dots, X_J) be the attractor of a strongly connected graph directed IFS*

$$A(X_i) = \bigcup_{j=1}^J (X_j + \mathcal{D}_{ij}), \quad i = 1, \dots, J.$$

Suppose that there exists an $\varepsilon_0 > 0$ such that the sets \mathcal{D}_{ij}^m have ε_0 -separation for all i, j, m , and X_1 has positive Lebesgue measure. Then every X_i has nonempty interior, and it is the closure of its interior.

Observe that all X_i have positive Lebesgue measures because of the strong connectivity of the graph directed IFS. Before proving Theorem 3.1 we first establish the following lemma:

Lemma 3.2 *Under the assumption of Theorem 3.1, let δ_m be a sequence of positive numbers whose limit is 0. Then there exist positive constants r_0 and c_0 such that for each $m \geq 1$ there exist finite subsets $\mathcal{E}_1^m, \dots, \mathcal{E}_J^m$ of \mathbb{R}^d contained in the ball $B_{r_0}(\mathbf{0})$, of cardinality at most c_0 with $\|\mathbf{e} - \mathbf{e}'\| \geq \varepsilon_0$ for all j, m and any distinct elements $\mathbf{e}, \mathbf{e}' \in \mathcal{E}_j^m$, such that*

$$\nu(B_1(\mathbf{0}) \cap Y_m) \geq (1 - 5^{d+1}\delta_m)\nu(B_1(\mathbf{0})) \quad (3.5)$$

where $Y_m := \bigcup_{j=1}^J (X_j + \mathcal{E}_j^m)$ and $B_1(\mathbf{0})$ is the Euclidean unit ball centered at the origin.

Proof. Since X_1 has positive Lebesgue measure, it has a Lebesgue point \mathbf{x}^* , i.e. there is a sequence $r_m \rightarrow 0$ such that

$$\nu(B_{r_m}(\mathbf{x}^*) \cap X_1) \geq (1 - \delta_m)\nu(B_{r_m}(\mathbf{x}^*)).$$

This implies that

$$\nu(A^l(B_{r_m}(\mathbf{x}^*)) \cap X_1) \geq (1 - \delta_m)\nu(A^l(B_{r_m}(\mathbf{x}^*))), \text{ for all } l \geq 0. \quad (3.6)$$

We first show that for sufficiently large l , there exists a unit ball $B_1(\mathbf{y}) \subset A^l(B_{r_m}(\mathbf{x}^*))$ with

$$\nu(B_1(\mathbf{y}) \cap A^l(X_1)) \geq (1 - 5^{d+1}\delta_m)\nu(B_1(\mathbf{0})). \quad (3.7)$$

Indeed, since A is expanding $A^l(B_{r_m}(\mathbf{x}^*))$ is an ellipsoid $O_{l,m}$ whose shortest axis goes to infinity as l goes to infinity. Let $O'_{l,m}$ be the homothetically shrunk ellipsoid with shortest axis decreased in length by 2, so that all points in it are at distant at least 1 from the boundary of $O_{l,m}$. By a standard covering lemma (cf. Stein [26, p. 9]) applied to $O'_{l,m}$ there is a set $\{B_1(\mathbf{y}')\}$ of disjoint unit balls with centers in $O'_{l,m}$ that cover volume at least $5^{-d}\nu(O'_{l,m})$. Notice that once the shortest axis of the ellipsoid $O_{l,m}$ has length greater than $2d + 1$ we will have $5^{-d}\nu(O'_{l,m}) \geq 5^{-d-1}\nu(O_{l,m})$, since $(\frac{d}{d+1})^d > 1/5$. All these balls lie inside $O_{l,m}$. By (3.6) at most $\delta_m\nu(A^l(B_{r_m}(\mathbf{x}^*)))$ of the volume of $A^l(B_{r_m}(\mathbf{x}^*))$ is uncovered by $A^l(B_{r_m}(\mathbf{x}^*) \cap X_1)$, so at least one of the disjoint balls $\{B_1(\mathbf{y}')\}$ must satisfy (3.7).

By (3.3) we can rewrite the inequality (3.7) as

$$\nu\left(B_1(\mathbf{y}) \cap \left(\bigcup_{j=1}^J (X_j + \mathcal{D}_{1j}^l)\right)\right) \geq (1 - 5^{d+1}\delta_m)\nu(B_1(\mathbf{y})),$$

therefore

$$\nu\left(B_1(\mathbf{y}) \cap \left(\bigcup_{j=1}^J (X_j + \mathcal{D}_{1j}^l - \mathbf{y})\right)\right) \geq (1 - 5^{d+1}\delta_m)\nu(B_1(\mathbf{0})),$$

This shows that if we choose

$$\mathcal{E}_j^m = \left\{ \mathbf{d} - \mathbf{y} \mid \mathbf{d} \in \mathcal{D}_{1j}^l \text{ with } (X_j + \mathbf{d} - \mathbf{y}) \cap B_1(\mathbf{0}) \neq \emptyset \right\}$$

then (3.5) holds. Since all \mathcal{D}_{ij}^m have ε_0 -separation, we have $\|\mathbf{e} - \mathbf{e}'\| \geq \varepsilon_0$ for all \mathbf{e}, \mathbf{e}' in \mathcal{E}_j^m . Since all X_j are compact, all \mathcal{E}_j^m are inside the ball $B_{r_0}(\mathbf{0})$ for some fixed $r_0 > 0$. The ball $B_{r_0}(\mathbf{0})$ can be packed with disjoint balls of radius $\varepsilon_0/2$ centered at the points of \mathcal{E}_j^m for each j . This implies that the cardinality of \mathcal{E}_j^m must be bounded by some constant c_0 . \blacksquare

Proof of Theorem 3.1. We apply the previous lemma and choose a subsequence m_k so that $\{\mathcal{E}_j^{m_k}\}$ converges for all j , and we denote the limit by \mathcal{E}_j^∞ . Clearly \mathcal{E}_j^∞ has cardinality at most c_0 . So

$$\begin{aligned} \nu\left(B_1(\mathbf{0}) \cap \left(\bigcup_{j=1}^J (X_j + \mathcal{E}_j^\infty)\right)\right) &\geq \liminf_{k \rightarrow \infty} \nu\left(B_1(\mathbf{0}) \cap \left(\bigcup_{j=1}^J (X_j + \mathcal{E}_j^{m_k})\right)\right) \\ &\geq \liminf_{k \rightarrow \infty} (1 - 5^{d+1}\delta_{m_k})\nu(B_1(\mathbf{0})) \\ &= \nu(B_1(\mathbf{0})). \end{aligned}$$

Since each $X_j + \mathcal{E}_j^\infty$ is a closed set, we must have

$$B_1(\mathbf{0}) \cap \left(\bigcup_{j=1}^J (X_j + \mathcal{E}_j^\infty) \right) = B_1(\mathbf{0}).$$

This means at least one of X_j 's must have interior. But if so then the strong connectivity implies that all X_j must have nonempty interior. Let $X'_j = \overline{X_j^\circ}$. Then (X'_1, \dots, X'_J) must also satisfy the same graph directed IFS. By the uniqueness (see Mauldin and Williams [16]) $X_j = X'_j$ for all j . \blacksquare

Theorem 3.3 *Let (X_1, \dots, X_J) be the attractor of a strongly connected graph directed IFS*

$$A(X_i) = \bigcup_{j=1}^J (X_j + \mathcal{D}_{ij}), \quad i = 1, \dots, J \quad (3.8)$$

with a primitive subdivision matrix S . Suppose that some X_i has nonempty interior, and $|\det A| = \rho(S)$ where $\rho(\cdot)$ is the spectral radius. Then (X_1, \dots, X_J) is a self-affine tile with respect to A and \mathcal{D}_{ij} .

Proof. By the primitivity of S we know that all X_i have nonempty interior. Hence $\nu(X_i) > 0$. Let $\mathbf{w} = [\nu(X_1), \dots, \nu(X_J)]^T$. Taking Lebesgue measure on both sides of (3.8) yields

$$|\det A| \mathbf{w} \leq S \mathbf{w} \quad (3.9)$$

with equality holding if and only if the unions on the right-hand side of (3.8) are all disjoint (measure-wise). But $|\det A|$ is the Perron-Frobenius eigenvector of S and $\mathbf{w} > 0$, so (3.9) must be an equality. Hence all unions on the right-hand side of (3.8) are measure-wise disjoint. Therefore (X_1, \dots, X_J) is a self-affine multi-tile with respect to A and \mathcal{D}_{ij} . \blacksquare

4 Rauzy Fractals

In this section we introduce a natural decomposition of a Rauzy fractal \mathfrak{R} . We show that this natural decomposition leads to a self-affine multi-tile using the results from §3. We derive several corollaries of this result.

For a Rauzy fractal $\mathfrak{R} = \overline{\{\Delta([\mathbf{U}]_m) : m \geq 0\}}$ let

$$\mathfrak{R}_i = \overline{\{\Delta([\mathbf{U}]_m) \mid \mathbf{U}(m+1) = i, m \geq 0\}}, \quad 1 \leq i \leq n. \quad (4.1)$$

Clearly $\bigcup_{i=1}^n \mathfrak{R}_i = \mathfrak{R}$. A better way to view \mathfrak{R} and \mathfrak{R}_i is to consider the ‘‘tail’’ of \mathbf{U} . For any valuation E corresponding to an eigenvalue $|\omega| < 1$ it is known that E can be extended naturally to a valuation on $\mathcal{A}^{\mathbb{N}}$ (see [9]). Since $\Pi(\mathbf{U}) = \mathbf{U}$ we have $E(\mathbf{U}) = \omega E(\mathbf{U})$, implying $E(\mathbf{U}) = 0$. Thus we may view \mathfrak{R} as

$$\mathfrak{R} = \overline{\{\Delta(\sigma^m \mathbf{U}) : m \geq 0\}}$$

and \mathfrak{R}_i as

$$\mathfrak{R}_i = -\overline{\left\{ \Delta(\sigma^m \mathbf{U}) \mid \mathbf{U}(m+1) = i, m \geq 0 \right\}}.$$

In other words, \mathfrak{R}_i is given by the shifts of \mathbf{U} whose beginning elements is the letter i . We shall call $(\mathfrak{R}_1, \dots, \mathfrak{R}_n)$ the *natural decomposition* of the Rauzy fractal \mathfrak{R} .

A key ingredient for proving our main theorem is to express the natural decomposition $(\mathfrak{R}_1, \dots, \mathfrak{R}_n)$ of a Rauzy fractal \mathfrak{R} in terms of the attractor of a graph directed IFS. This fact is proved in [9]. Let $F = \{(j, k) : j \in \mathcal{A}, 1 \leq k \leq |\Pi(j)|\}$ where $|U|$ denote the length of U for $U \in \mathcal{A}^*$, and let $F_i = \{(j, k) \in F : \Pi(j)(k) = i\}$, where $\Pi(j)(k)$ denotes the k -th symbol of $\Pi(j)$. Then $(\mathfrak{R}_1, \dots, \mathfrak{R}_n)$ satisfies

$$\mathfrak{R}_i = \bigcup_{(j,k) \in F_i} \left(B\mathfrak{R}_j + \Delta([\Pi(j)]_{k-1}) \right), \quad i = 1, \dots, n, \quad (4.2)$$

where $B = \text{diag}(\omega_1, \omega_2, \dots, \omega_r)$ with ω_j being defined in (1.4). Recall also that for any word U in \mathcal{A}^* the notation $[U]_m$ denotes the word formed by the first m letters of U , with $[U]_0 := \emptyset$. It is shown in addition in [9] that the graph directed IFS (4.2) is strongly connected in the sense that its subdivision matrix (defined below) is primitive, see [9] for details.

Our main theorem shows that the natural decomposition $(\mathfrak{R}_1, \dots, \mathfrak{R}_n)$ forms a self-affine multi-tile.

Theorem 4.1 *Let \mathfrak{R} be a Rauzy fractal associated to a fixed point of a primitive and unimodular Pisot substitution in $n \geq 2$ symbols. Then the natural decomposition $(\mathfrak{R}_1, \mathfrak{R}_2, \dots, \mathfrak{R}_n)$ of \mathfrak{R} is a self-affine multi-tile. Furthermore $\mathfrak{R}_i = \overline{\mathfrak{R}_i^c}$ for all $1 \leq i \leq n$.*

Proof. We already know that $(\mathfrak{R}_1, \dots, \mathfrak{R}_n)$ is the attractor of the strongly connected graph directed IFS (4.2), which is rewritten as

$$B^{-1}(\mathfrak{R}_i) = \bigcup_{(j,k) \in F_i} \left(\mathfrak{R}_j + B^{-1}(\Delta([\Pi(j)]_{k-1})) \right), \quad i = 1, \dots, n. \quad (4.3)$$

Note that by (2.1) for each $j \in \mathcal{A}$ there exists a $g_j(x) \in \mathbb{Z}[x]$ and fixed constants c_1, \dots, c_r such that

$$B^{-1}\Delta(j) = [\omega_1^{-1}g_j(\omega_1)c_1, \dots, \omega_r^{-1}g_j(\omega_r)c_r]^T.$$

As in the proof of Lemma 2.6, we may choose a sufficiently large but fixed N such that

$$B^{-1}\Delta(j) = [\omega_1^N f_j(\omega_1)c_1, \dots, \omega_r^N f_j(\omega_r)c_r]^T = D_0 \boldsymbol{\omega}_{f_j},$$

for some $f_j \in \mathbb{Z}[x]$, where $D_0 = \text{diag}(\omega_1^N c_1, \dots, \omega_r^N c_r)$. This means that if we write (4.3) as

$$B^{-1}(\mathfrak{R}_i) = \bigcup_{j=1}^n \left(\mathfrak{R}_j + \mathcal{D}_{ij} \right), \quad i = 1, \dots, n,$$

then each \mathcal{D}_{ij} is either empty, or all its elements have the form $D_0 \boldsymbol{\omega}_f$ for some finite collection of polynomials $f(x) \in \mathbb{Z}[x]$. Hence by Corollary 2.4 and (3.4) there exists an $\varepsilon_0 > 0$ such

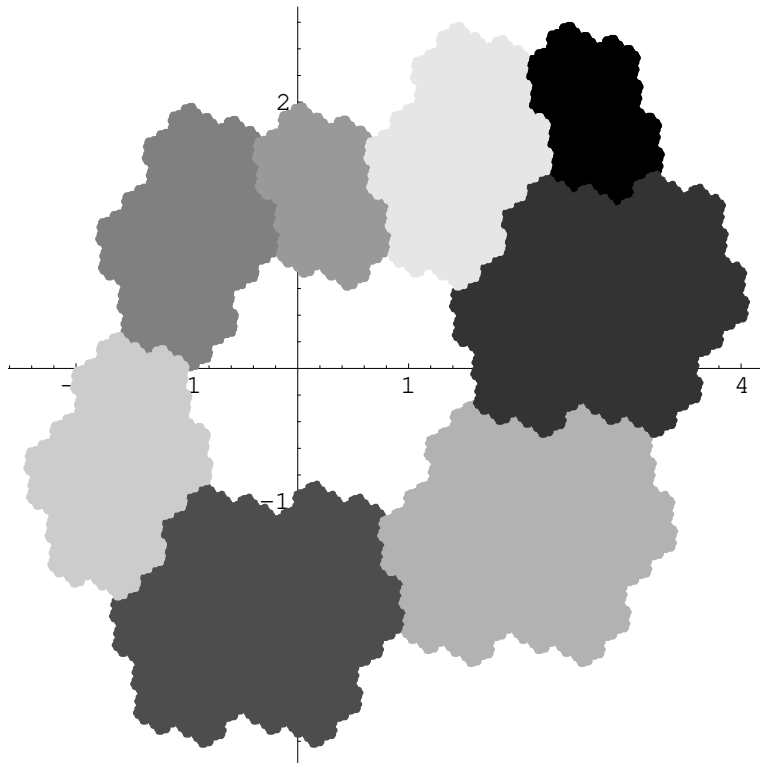


Figure 3: Tiling for the substitution $1 \rightarrow 12, 2 \rightarrow 13, 3 \rightarrow 1$.

that all \mathcal{D}_{ij}^m are ε_0 -separated. Since the graph directed IFS (4.2) is strongly connected and $\nu(\mathfrak{X}_i) > 0$ for some i , it now follows from Theorem 3.1 that $\overline{\mathfrak{X}_i^o} \neq \emptyset$ and $\overline{\mathfrak{X}_i^o} = \mathfrak{X}_i$ for all i . Now observe that the subdivision matrix of the graph directed IFS (4.3) is precisely M^T , where M is the incidence matrix of the substitution. Taking the Lebesgue measure on both side of (4.3), using (2.5), we obtain

$$\lambda \mathbf{w} \leq M^T \mathbf{w}, \quad (4.4)$$

where $\mathbf{w} = [\nu(\mathfrak{X}_1), \dots, \nu(\mathfrak{X}_n)]^T$, with equality holding if and only if the unions on the right-hand side of (4.3) are all disjoint (measure-wise). But λ is the Perron-Frobenius eigenvector of M^T and $\mathbf{w} > 0$, so (4.4) must be an equality. Hence all unions on the right-hand side of (4.3) are measure-wise disjoint. Therefore $(\mathfrak{X}_1, \dots, \mathfrak{X}_n)$ is a self-affine multi-tile with respect to B and

$$\mathcal{D}_{ij} := \left\{ B^{-1}(\Delta([\Pi(j)]_{k-1})) : (j, k) \in F_i \right\}.$$

■

Corollary 4.2 *Let \mathfrak{X} be a Rauzy fractal associated to a fixed point of a primitive and unimodular Pisot substitution in $n \geq 2$ symbols. Then \mathfrak{X} has nonempty interior and $\mathfrak{X} = \overline{\mathfrak{X}^o}$.*

The tilings associated to the examples 2.1 and 2.2 are shown in figures 3 and 4.

Corollary 4.3 *Let \mathfrak{X} be a Rauzy fractal associated to a fixed pint of a primitive and unimodular Pisot substitution in $n \geq 2$ symbols. Then there exist infinite discrete sets $\mathcal{J}_1, \dots, \mathcal{J}_n \subset \mathbb{C}^p \times \mathbb{R}^{r-p}$ such that*

$$\bigcup_{i=1}^n \bigcup_{\mathbf{j} \in \mathcal{J}_i} (\mathfrak{X}_i + \mathbf{j}) = \mathbb{C}^p \times \mathbb{R}^{r-p} \quad (4.5)$$

is a tiling of $\mathbb{C}^p \times \mathbb{R}^{r-p}$.

Proof. The corollary follows from the standard technique of repeated iteration of (4.3). The existence of the infinite discrete sets $\mathcal{J}_1, \dots, \mathcal{J}_n$ of $\mathbb{C}^p \times \mathbb{R}^{r-p}$ such that

$$\bigcup_{i=1}^n \bigcup_{\mathbf{j} \in \mathcal{J}_i} (\mathfrak{X}_i + \mathcal{J}_i) = \mathbb{C}^p \times \mathbb{R}^{r-p}$$

is a tiling of $\mathbb{C}^p \times \mathbb{R}^{r-p}$ is proved in Flaherty and Wang [6].

■

An interesting unsolved problem concerns the measure disjointness of the natural decomposition of a Rauzy fractal \mathfrak{X} . Here we state it explicitly as a conjecture:

Conjecture *Let \mathfrak{X} be a Rauzy fractal associated to a fixed pint of a primitive and unimodular Pisot substitution in $n \geq 2$ symbols. Let $(\mathfrak{X}_1, \dots, \mathfrak{X}_n)$ be the natural decomposition of \mathfrak{X} . Then all \mathfrak{X}_i are measure-wise disjoint.*

Figure 4: Tiling for the substitution $1 \rightarrow 12, 2 \rightarrow 3, 3 \rightarrow 1$.

The above conjecture has been studied in Arnoux and Ito [1]. It is shown there that the disjointness of the natural decomposition is equivalent to a combinatorial condition called the *positive strong coincidence* condition. A substitution Π is said to satisfy the positive strong coincidence condition if for any two letters j_1 and j_2 in \mathcal{A} there exist a letter i and integers $m, k_1, k_2 \geq 1$ such that

$$\Pi^m(j_1)(k_1) = \Pi^m(j_2)(k_2) = i \quad \text{and} \quad \Delta([\Pi^m(j_1)]_{k_1-1}) = \Delta([\Pi^m(j_2)]_{k_2-1}).$$

We state their theorem below, and show that the connection with self-affine multi-tiles also yield a simple proof of the result.

Theorem 4.4 (Arnoux and Ito) *Let \mathfrak{R} be a Rauzy fractal associated to a fixed point \mathbf{U} of a primitive and unimodular Pisot substitution Π in $n \geq 2$ symbols. Let $(\mathfrak{R}_1, \dots, \mathfrak{R}_n)$ be the natural decomposition of \mathfrak{R} . Suppose that Π satisfies the positive strong coincidence condition. Then all \mathfrak{R}_i are measure-wise disjoint.*

Proof. We prove the measure-wise disjointness of $\{\mathfrak{R}_i\}$ using the special property that a Rauzy fractal for the substitution Π is also a Rauzy fractal for the substitution Π^m , $m \geq 1$. This follows easily from the fact that if $\Pi(\mathbf{U}) = \mathbf{U}$ then $\Pi^m(\mathbf{U}) = \mathbf{U}$, and the fact that a valuation on $\Omega_{\mathbf{U}}$ for Π with respect to an ω -eigenvector \mathbf{v} is also a valuation on $\Omega_{\mathbf{U}}$ for Π^m with respect to the ω^m -eigenvector \mathbf{v} .

Notice that the natural decomposition $(\mathfrak{R}_1, \dots, \mathfrak{R}_n)$ of \mathfrak{R} as a Rauzy fractal for Π is also the natural decomposition of \mathfrak{R} as a Rauzy fractal for Π^m , since it depends only on the valuation vector Δ , which is the same for both cases. Now, Π^m has incidence matrix M^m where M is the incidence matrix of Π . Clearly, Π^m is also primitive and unimodular Pisot, with the Pisot eigenvalue λ^m and its conjugates

$$\omega_1^m, \bar{\omega}_1^m, \dots, \omega_p^m, \bar{\omega}_p^m, \omega_{p+1}^m, \dots, \omega_r^m$$

where ω_j are as in (1.4). So $(\mathfrak{R}_1, \dots, \mathfrak{R}_n)$ satisfies

$$\mathfrak{R}_i = \bigcup_{(j,k) \in F_i^m} \left(B^m \mathfrak{R}_j + \Delta([\Pi^m(j)]_{k-1}) \right), \quad i = 1, \dots, n, \quad (4.6)$$

where $B = \text{diag}(\omega_1, \omega_2, \dots, \omega_r)$ and $F_i^m = \{(j, k) : \Pi^m(j)(k) = i\}$, with the unions on the right side of (4.6) measure-wise disjoint. Since Π satisfies the positive strong coincidence

condition, for any two letters j_1 and j_2 in \mathcal{A} there exist a letter i and integers $m, k_1, k_2 \geq 1$ such that

$$\Pi^m(j_1)(k_1) = \Pi^m(j_2)(k_2) = i \quad \text{and} \quad \Delta([\Pi^m(j_1)]_{k_1-1}) = \Delta([\Pi^m(j_2)]_{k_2-1}).$$

Therefore the unions on the right side of (4.6) contain the terms $B^m\mathfrak{R}_{j_1} + \mathbf{d}$ and $B^m\mathfrak{R}_{j_2} + \mathbf{d}$, where $\mathbf{d} = \Delta([\Pi^m(j_1)]_{k_1-1}) = \Delta([\Pi^m(j_2)]_{k_2-1})$. Hence $B^m\mathfrak{R}_{j_1}$ and $B^m\mathfrak{R}_{j_2}$ are measure-wise disjoint, and so \mathfrak{R}_{j_1} and \mathfrak{R}_{j_2} are measure-wise disjoint. This proves the theorem. ■

The positive strong coincidence condition is very difficult to verify in general. We verify it for a special case, in which the substitution Π has a unique periodic point \mathbf{U} .

Corollary 4.5 *Let \mathfrak{R} be a Rauzy fractal associated to a fixed pint \mathbf{U} of a primitive and unimodular Pisot substitution Π in $n \geq 2$ symbols. Suppose that \mathbf{U} is the unique fixed point of Π^m for all $m \geq 1$. Then the natural decomposition $(\mathfrak{R}_1, \dots, \mathfrak{R}_n)$ of \mathfrak{R} is measure-wise disjoint.*

Proof. Without loss of generality we assume that $\mathbf{U}(1) = 1$. This means that there exists an $m \geq 1$ such that all $\Pi^m(j)$ begins with the letter 1. Therefore Π satisfies the positive strong coincidence condition by taking $i = 1$ and $k_1 = k_2 = 1$. ■

References

- [1] P. Arnoux and S. Ito, Pisot substitutions and Rauzy fractals, Pre-print, IML 98-18.
- [2] M.F. Barnsley, *Fractals everywhere*, Second Edition, Academic Press Professional, London, 1993.
- [3] V. Canterini and A. Siegel, Automate des préfixes-suffixes associé à une substitution primitive, Preprint of IML 99-27.
- [4] V. Canterini and A. Siegel, Geometric Representation of primitive substitution of Pisot type, Preprint of IML 2000-02.
- [5] F.M. Dekking, Recurrent Sets, *Adv. Math.* **44** (1982), 78-104.
- [6] T. Flaherty and Y. Wang, Haar-type multiwavelet bases and self-affine multi-tiles, *Asian J. Math.* **3** (1999), no. 2, 387-400.
- [7] K. Gröchenig and A. Haas, Self-similar lattice tilings, *J. Fourier Anal. Appl.* **1** (1994), 131-170.
- [8] K. Gröchenig, A. Haas and A. Raugi, Self-affine tilings with several tiles. I., *Appl. Comput. Harmon. Anal.* **7** (1999), no. 2, 211-238.
- [9] C. Holton and L. Zamboni, Geometric realization of substitutions, *Bull. Soc. Math. France*, **126** (1998), 149-179.
- [10] J.E. Hutchinson, Fractals and self-similarity, *Indiana U. Math. J.* **30** (1981), 713-747.

- [11] R. Kenyon, Self-replicating tilings, in: *Symbolic Dynamics and Applications* (P. Walters, ed.) Contemporary Math. vol. 135 (1992), 239-264.
- [12] R. Kenyon, The construction of self-similar tilings, *Geom. Funct. Anal.* **6** (1996), no. 3, 471-488.
- [13] R. Kenyon and A. Vershik, Arithmetic construction of sofic partitions of hyperbolic toral automorphisms, *Ergodic Theory Dynam. Systems* **18** (1998), no. 2, 357-372.
- [14] J.C. Lagarias and Y. Wang, Self-affine tiles in \mathbb{R}^n . *Adv. Math.* **121** (1996), 21-49.
- [15] J.C. Lagarias and Y. Wang, Substitution delone sets, preprint.
- [16] R.D. Mauldin and S.C. Williams, Hausdorff dimension in graph directed constructions, *Trans. of the Amer. Math. Soc.* **309** (1988), 811-829.
- [17] A. Messaoudi, Frontière du fractal de Rauzy et système de numération complexe, *Acta Arith.* **95** (2000), 195-224.
- [18] C. Petronio, Thurston's solitaire tilings of the plane. *Rend. Istit. Mat. Univ. Trieste* **26** (1994) 261-295.
- [19] B. Praggastis, Numeration systems and Markov partitions from self-similar tilings, *Trans. Amer. Math. Soc.* **351** (1999), 3315-3349.
- [20] M. Queffélec, *Substitution Dynamical Systems -Spectral Analysis*, Lecture Notes in Mathematics, Vol 1294, Springer-Verlag, 1987, Berlin.
- [21] M. Queffélec, Spectral study of automatic and substitutive sequences. *Beyond quasicrystals (Les Houches, 1994)*, 369-414, Springer, Berlin, 1995.
- [22] C. Radin, Space tilings and substitutions, *Geom. Dedicata* **55** (1995), 257-264.
- [23] G. Rauzy, Nombres algébriques et substitutions, *Bull. Soc. Math. France* **110** (1982), 147-178.
- [24] G. Rauzy, Sequences Defined by Iterated Morphisms, in *Sequences* (Napoles/Positano, 1988), Edited by R.M. Capocelli, Springer, New York, 1990, 275-286.
- [25] G. Rauzy, Rotations sur les groupes, nombres algébriques et substitutions, *Séminaire de théorie des nombres de Bordeaux* **21** (1988), 1-12.
- [26] E. Stein, *Singular Integrals and Differentiability Properties of Functions*, Princeton Univ. Press, Princeton, NJ, 1970.
- [27] V.F. Sirvent, Relationships between the dynamical systems associated to the Rauzy substitutions, *Theoret. Comput. Sci.* **164** (1996), 41-57.
- [28] V.F. Sirvent, On some dynamical subsets of the Rauzy Fractal, *Theoret. Comput. Sci.* **180** (1997), 363-370.
- [29] V.F. Sirvent, Identifications and dimension of the Rauzy Fractal, *Fractals* **5** (1997), 281-294.
- [30] B. Solomyak, A dynamical system with a discrete spectrum (Russian), *Uspekhi Mat. Nauk* **41** (1986), 209-210. English translation: *Russian Math. Surveys* **41** (1986), 219-220.
- [31] B. Solomyak, Substitutions, adic transformations, and beta-expansions, *Symbolic dynamics and its applications*(New Haven, CT, 1991), 361-372, *Contemp. Math.*, **135**, AMS, Providence, 1992.

- [32] B. Solomyak, *On the spectral theory of adic transformations*, *Advances in Soviet Mathematics*, **9** (1992), 217-230.
- [33] B. Solomyak, Dynamics of self-similar tilings, *Ergodic Theory Dynam. Systems*, **17**, (1997), no. 3, 695–738.
- [34] W. Thurston, Groups, tilings, and finite state automata, *AMS Colloquium Lecture Notes*, unpublished, 1889.
- [35] A. Vince, Replicating tessellations, *SIAM J. Discrete Math* **6** (1993), 501-521.