POINTWISE HÖLDER EXPONENTS OF THE COMPLEX ANALOGUES OF THE TAKAGI FUNCTION IN RANDOM COMPLEX DYNAMICS

JOHANNES JAERISCH AND HIROKI SUMI

ABSTRACT. We consider hyperbolic random complex dynamical systems on the Riemann sphere with separating condition and multiple minimal sets. We investigate the Hölder regularity of the function $T$ of the probability of tending to one minimal set, the partial derivatives of $T$ with respect to the probability parameters, which can be regarded as complex analogues of the Takagi function, and the higher partial derivatives $C$ of $T$. Our main result gives a dynamical description of the pointwise Hölder exponents of $T$ and $C$, which allows us to determine the spectrum of pointwise Hölder exponents by employing the multifractal formalism in ergodic theory. Also, we prove that the bottom of the spectrum $\alpha_-$ is strictly less than 1, which allows us to show that the averaged system acts chaotically on the Banach space $C^\alpha$ of $\alpha$-Hölder continuous functions for every $\alpha \in (\alpha_- , 1)$, though the averaged system behaves very mildly (e.g. we have spectral gaps) on $C^\beta$ for small $\beta > 0$. 

1. INTRODUCTION AND STATEMENT OF RESULTS

In this paper, we consider random dynamical systems of rational maps on the Riemann sphere $\hat{\mathbb{C}}$. The study of random complex dynamics was initiated by J.E. Fornaess and N. Sibony ([FS91]). There are many new interesting phenomena in random dynamical systems, so called randomness-induced phenomena or noise-induced phenomena, which cannot hold in the deterministic iteration dynamics. For the motivations and recent research of random complex dynamical systems focused on the randomness-induced phenomena, see the second author's works [Sum11a, Sum13, Sumi15a, Sumi15b]. In these papers it was shown that for a generic random dynamical system of complex polynomials, the system acts very mildly on the space of continuous functions on $\hat{\mathbb{C}}$ and on the space $C^\alpha(\hat{\mathbb{C}})$ for small $\alpha \in (0,1)$, where $C^\alpha(\hat{\mathbb{C}})$ denotes the Banach space of $\alpha$-Hölder continuous functions on $\hat{\mathbb{C}}$ endowed with $\alpha$-Hölder norm, but under certain conditions the system still acts chaotically on the space $C^\beta(\hat{\mathbb{C}})$ for some $\beta \in (0,1)$ close to 1. Thus, we investigate the gradation between chaos and order in random (complex) dynamical systems.

In order to show the main ideas of the paper, let $\text{Rat}$ denote the set of all non-constant rational maps on $\hat{\mathbb{C}}$. This is a semigroup whose semigroup operation is the composition of maps. Throughout the paper, let $s \geq 1$ and let $(f_1, \ldots, f_{s+1}) \in (\text{Rat})^{s+1}$ with $\deg(f_i) \geq 2, i = 1, \ldots, s + 1$. Let $p = (p_1, \ldots, p_s) \in (0, 1)^s$ with $\sum_{i=1}^s p_i < 1$ and let $p_{s+1} := 1 - \sum_{i=1}^s p_i$. We consider the (i.i.d.) random dynamical system on $\hat{\mathbb{C}}$ such that at every step we choose $f_i$ with probability $p_i$. This defines a Markov chain with state space $\hat{\mathbb{C}}$ such that for each $x \in \hat{\mathbb{C}}$ and for each Borel measurable subset $A$ of $\hat{\mathbb{C}}$, the transition probability $p(x, A)$ from $x$ to $A$ is equal to $\sum_{i=1}^{s+1} p_i 1_A(f_i(x))$, where $1_A$ denotes the characteristic function of $A$. Let $G = \langle f_1, \ldots, f_s, f_{s+1} \rangle$ be the rational semigroup (i.e., subsemigroup of $\text{Rat}$) generated by $\{f_1, \ldots, f_{s+1}\}$. More precisely, $G = $ 

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Johannes Jaerisch
Department of Mathematics, Faculty of Science and Engineering, Shimane University, Nishikawatsu 1060 Matsue, Shimane 690-8504, Japan E-mail: jaerisch@riko.shimane-u.ac.jp Web: http://www.math.shimane-u.ac.jp/~jaerisch/

Hiroki Sumi (corresponding author)
Department of Mathematics, Graduate School of Science, Osaka University, 1-1 Machikaneyama, Toyonaka, Osaka, 560-0043, Japan E-mail: sumi@math.sci.osaka-u.ac.jp Web: http://www.math.sci.osaka-u.ac.jp/~sumi/.
\[ \{ f_{\omega_1} \circ \cdots \circ f_{\omega_s} : n \in \mathbb{N}, \omega_1, \ldots, \omega_s \in \{1, \ldots, s+1\} \}. \]

We denote by \( F(G) \) the maximal open subset of \( \hat{C} \) on which \( G \) is equicontinuous with respect to the spherical distance on \( \hat{C} \). The set \( F(G) \) is called the Fatou set of \( G \), and the set \( J(G) := \hat{C} \setminus F(G) \) is called the Julia set of \( G \). We remark that in order to investigate random complex dynamical systems, it is very important to investigate the dynamics of associated rational semigroups. The first study of dynamics of rational semigroups was conducted by A. Hinkkanen and G. J. Martin ([HMM96]), who were interested in the role of polynomial semigroups (i.e., semigroups of non-constant polynomial maps) while studying various one-complex-dimensional moduli spaces for discrete groups, and by F. Ren’s group ([GR96]), who studied such semigroups from the perspective of random dynamical systems. For the interplay of random complex dynamics and dynamics of rational semigroups, see [Sum00], [Sum15b], [SS11], [SU13], [JS15a], [JS15b].

Throughout the paper, we assume the following.

1. \( G \) is hyperbolic, i.e., we have \( P(G) \subset F(G) \), where

\[
\begin{align*}
P(G) := \bigcup_{g \in G \setminus \{ id \}} g(\bigcup_{i=1}^{s+1} \{ \text{critical values of } f_i : \hat{C} \to \hat{C} \}).
\end{align*}
\]

Here, the closure is taken in \( \hat{C} \).

2. \( (f_1, \ldots, f_{s+1}) \) satisfies the separating condition, i.e., \( f_i^{-1}(J(G)) \cap f_j^{-1}(J(G)) = \emptyset \) whenever \( i, j \in \{1, \ldots, s+1\}, i \neq j \).

3. There exist at least two minimal sets of \( G \). Here, a non-empty compact subset \( K \) of \( \hat{C} \) is called a minimal set of \( G \) if \( K = \bigcup_{g \in G} \{ g(z) \} \) for each \( z \in K \).

Note that by assumption (2), [Sum97, Lemma 1.1.4] and [Sum11a, Theorem 3.15], we have that there exist at most finitely many minimal sets of \( G \). Moreover, denoting by \( S_G \) the union of minimal sets of \( G \) and setting \( I := \{1, \ldots, s+1\} \), we have that for each \( z \in \hat{C} \) there exists a Borel subset \( A_z \) of \( \mathbb{P} \) with \( \mu_p(A_z) = 1 \) such that \( d(f_{\omega_1} \cdots f_{\omega_s}(z), S_G) \to 0 \) as \( n \to \infty \) for all \( \omega = (\alpha_i)_{i=1}^{s+1} \in A_z \), where \( \mu_p := \otimes_{i=1}^{s+1} \mu_p \) denotes the product measure on \( \mathbb{P} \) given by \( \mu_p \ := \sum_{i=1}^{s+1} p_i \delta_i \) with \( \delta_i \) denoting the Dirac measure concentrated at \( i \in I \).

Throughout, we fix a minimal set \( L \) of \( G \) (e.g. \( L = \{ \infty \} \) when \( G \) is a polynomial semigroup). Denote by \( T_p(z) \) the probability of tending to \( L \) of the process on \( \hat{C} \) which starts in \( z \in \hat{C} \) and which is given by drawing independently with probability \( p_i \) the map \( f_i \). More precisely, \( T_p(z) := \hat{\mu}_p(\{ \omega = (\alpha_i)_{i=1}^{s+1} \in \mathbb{P} : d(f_{\omega_1} \cdots f_{\omega_s}(z), L) \to 0 \text{ as } n \to \infty \}) \). It was shown by the second author in [Sum13] that, for each \( p = (p_1, \ldots, p_s) \) there exists \( \alpha \in (0, 1) \) such that \( x = (x_1, \ldots, x_s) \mapsto T_{(x_1, \ldots, x_s, 1)} \) is real-analytic in a neighbourhood of \( p \), where \( C^\alpha(\hat{C}) \) denotes the \( \mathbb{C} \)-Banach space of \( \alpha \)-Hölder continuous \( \mathbb{C} \)-valued functions on \( \hat{C} \) endowed with \( \alpha \)-Hölder norm \( \| \cdot \|_\alpha \) (Remark 1.17). Thus it is very natural and important to consider the following. For \( N_0 := \mathbb{N} \cup \{0\} \) and \( n = (n_1, \ldots, n_s) \in N_0^s \) we denote by \( C_n \in C^\alpha(\hat{C}) \) the higher order partial derivative of \( T_p \) of order \( |n| := \sum_{i=1}^s n_i \) with respect to the probability parameters given by

\[
C_n(z) := \frac{\partial^{|n|} T_{(x_1, \ldots, x_s, 1)}(z)}{\partial x_1^{n_1} \partial x_2^{n_2} \cdots \partial x_s^{n_s}} \bigg|_{x=p} \quad z \in \hat{C}.
\]

These functions are introduced in [Sum13] by the second author. We introduce the \( \mathbb{C} \)-vector space

\[
\mathcal{C} := \text{span} \{ C_n \mid n \in N_0^s \} \subset C^\alpha(\hat{C}),
\]

which consists of all the finite complex linear combinations of elements from \( \{ C_n \mid n \in N_0^s \} \). The first order derivatives are called complex analogues of the Takagi function in [Sum13]. Note that \( C_0 = T_p \).

For an element \( C \in \mathcal{C} \) and \( z \in \hat{C} \) the Hölder exponent \( \text{Hö}l(C, z) \) is given by

\[
\text{Hö}l(C, z) := \sup \left\{ \alpha \in [0, \infty) : \limsup_{\substack{y \to z, y \neq z}} \frac{|C(y) - C(z)|}{d(y, z)^\alpha} < \infty \right\} \in [0, \infty],
\]

where \( d \) denotes the spherical distance on \( \hat{C} \). It was shown in [JS15a] that the level sets
Theorem 1.1. For every non-trivial $C = \sum_{n \in \mathbb{N}} \beta_n C_n \in \mathcal{C}$ we have
\begin{equation}
H(\alpha, \mathcal{C}) := \{ z \in \hat{\mathcal{C}} : \text{Hölder}(\alpha, z) = \alpha \}, \quad \alpha \in \mathbb{R},
\end{equation}
satisfy the multifractal formalism. In particular, there exists an interval of parameters $(\alpha_-, \alpha_+)$ such that the Hausdorff dimension of $H(\alpha, \mathcal{C})$ is positive and varies real analytically (see Theorem 1.2 below).

The first main result of this paper gives a dynamical description of the pointwise Hölder exponents for an arbitrary $C \in \mathcal{C}$. We say that $C = \sum_{n \in \mathbb{N}} \beta_n C_n \in \mathcal{C}$ is non-trivial if there exists $n \in \mathbb{N}_0$ with $\beta_n \neq 0$. It turns out in Theorem 1.1 below that every non-trivial $C \in \mathcal{C}$ has the same pointwise Hölder exponents. To state the result, we define the skew product map (associated with $(f_i)_{i \in I}$) (see [Sum00])
\[
\tilde{f} : f^I \times \hat{\mathcal{C}} \to f^I \times \hat{\mathcal{C}}, \quad \tilde{f}(\omega, z) := (\sigma(\omega), f_{\omega_0}(z)),
\]
where $\sigma : f^I \to f^I$ denotes the shift map given by $\sigma(\omega_1, \omega_2, \ldots) = (\omega_2, \omega_3, \ldots)$, for $\omega = (\omega_1, \omega_2, \ldots) \in f^I$. For every $\omega = (\omega_i)_{i \in I} \in f^I$ and $n \in \mathbb{N}$, let $f_{\omega_n} := f_{\omega_0} \circ \cdots \circ f_{\omega_n}$ and we denote by $F_\omega$ the maximal open subset of $\hat{\mathcal{C}}$ on which $\{f_{\omega_n}\}_{n \in \mathbb{N}}$ is equicontinuous with respect to $d$. Let $J_\omega := \hat{\mathcal{C}} \setminus F_\omega$. The Julia set of $\tilde{f}$ is given by $J(\tilde{f}) = \bigcup_{\omega \in f^I} \{ \omega \} \times J_\omega$ where the closure is taken in $f^I \times \hat{\mathcal{C}}$. Note that denoting by $\pi : f^I \times \hat{\mathcal{C}} \to \hat{\mathcal{C}}$ the canonical projection, $\pi : J(\tilde{f}) \to J(G)$ is a homeomorphism ([Sum11a, Lemma 4.5], [Sum97, Lemma 1.1.4] and assumption (2)) and $\pi \circ \sigma = \sigma \circ \pi$. We introduce the potentials $\phi, \psi : J(\tilde{f}) \to \mathbb{R}$ given by
\[
\phi(\omega, z) := -\log \|f_{\omega_0}(z)\|, \quad \psi(\omega, z) := \log p_{\omega_0},
\]
where $\|\cdot\|$ denotes the norm of the derivative with respect to the spherical metric on $\hat{\mathcal{C}}$. Note that $\tilde{f}^{-1}(J(\tilde{f})) = J(\tilde{f}) = J(\tilde{f}) (\text{Sum00})$. We denote by $S_n$ the ergodic sum of the dynamical system $(J(\tilde{f}), \tilde{f})$.

**Theorem 1.1.** For every non-trivial $C = \sum_{n \in \mathbb{N}} \beta_n C_n \in \mathcal{C}$ we have
\[
(1.1) \quad H^\alpha(C, z) = \liminf_{k \to \infty} \frac{\log S_k \psi(\omega, z)}{\log S_k \phi(\omega, z)}, \quad \text{for all } (\omega, z) \in J(\tilde{f}).
\]
Combining Theorem 1.1 with our results from [JS15a, Theorem 1.2] on the multifractal formalism, we establish the multifractal formalism for the pointwise Hölder exponents of an arbitrary non-trivial $C \in \mathcal{C}$.

To state the results, for any non-trivial $C \in \mathcal{C}$ and $\alpha \in \mathbb{R}$ we denote by
\[
H(\alpha, \mathcal{C}) := \{ y \in \hat{\mathcal{C}} : \text{Hölder}(\alpha, y) = \alpha \}
\]
the level set of prescribed Hölder exponent $\alpha$. The range of the multifractal spectrum is given by
\[
\alpha_- := \inf \{ \alpha \in \mathbb{R} : H(\alpha, \mathcal{C}) \neq \emptyset \} \in \mathbb{R} \quad \text{and} \quad \alpha_+ := \sup \{ \alpha \in \mathbb{R} : H(\alpha, \mathcal{C}) \neq \emptyset \} \in \mathbb{R}.
\]
By Theorem 1.1, the sets $H(\alpha, \mathcal{C})$ coincide for all non-trivial $C \in \mathcal{C}$. Thus, $\alpha_-$ and $\alpha_+$ do not depend on the choice of a non-trivial $C \in \mathcal{C}$. Also, $\alpha_- > 0$ ([Sum98, Theorem 2.6], see also Corollary 1.11).

**Theorem 1.2** (For the detailed statements, see Theorem 6.1). All of the following hold.

1. Let $C \in \mathcal{C}$ be non-trivial. If $\alpha_- < \alpha_+$, then the Hausdorff dimension function $\alpha \mapsto \dim_H(\alpha, \mathcal{C})$, $\alpha \in (\alpha_-, \alpha_+)$, defines a real analytic and strictly concave positive function on $(\alpha_-, \alpha_+)$ with maximum value $\dim_H(J(G))$. If $\alpha_- = \alpha_+$, then we have $H(\alpha, \mathcal{C}) = J(G)$.

2. We have $\alpha_- = \alpha_+$ if and only if there exist an automorphism $\theta \in \text{Aut}(\hat{\mathcal{C}})$, complex numbers $(a_i)_{i \in I}$ and $\lambda \in \mathbb{R}$ such that for all $i \in I$ and $z \in \hat{\mathcal{C}},$
\[
\theta \circ f_i \circ \theta^{-1}(z) = a_i z^{\pm \deg(f_i)} \quad \text{and} \quad \log \deg(f_i) = \lambda \log p_i.
\]
In the next theorem we determine the actual Hölder class of every non-trivial $C \in \mathcal{C}$.

**Theorem 1.3.** For every non-trivial $C \in \mathcal{C}$ and for every $\alpha < \alpha_-$, the function $C$ is $\alpha$-Hölder continuous on $\hat{\mathcal{C}}$. Moreover, $C_0$ is $\alpha_-$-Hölder continuous on $\hat{\mathcal{C}}$. 

To prove Theorem 1.3 we develop some ideas from [KS08, JKPS09] for interval maps. The relation between the Hölder continuity of singular measures and their multifractal spectra has been first observed in [KS08], where it was shown that the Hölder continuity of the Minkowski’s question mark function coincides with the bottom of the Lyapunov spectrum of the Farey map. In [JKPS09] a similar result has been obtained for expanding interval maps.

In the following Theorem 1.4 we prove that \( \alpha_- < 1 \). This result allows us to give a complete answer to two important problems raised in [Sum13], which greatly improves the previous partial results in [Sum11a, Sum13, JS15a]. The first implication is that, under the assumptions of our paper, every non-trivial \( C \in \mathcal{C} \) is not differentiable at every point of a Borel dense subset \( A \) of \( J(G) \) with \( \dim_H(A) > 0 \). Secondly, we obtain in Theorem 1.5 that the averaged system still acts chaotically on the space \( C^α(\mathring{C}) \) for any \( \alpha \in (\alpha_-, 1) \), although the averaged system acts very mildly on the Banach space \( C(\mathring{C}) \) of \( C \)-valued continuous functions on \( \mathring{C} \) endowed with the supremum norm and on the Banach space \( C^α(\mathring{C}) \) for small \( \alpha > 0 \) (see [Sum97, Lemma 1.1.4], [Sum11a, Theorem 3.15] and [Sum13, Theorem 1.10]). We recall that if \( \text{Hö}(C, z) < 1 \) then \( C \) is differentiable at \( z \) and the derivative of \( C \) at \( z \) is zero.

**Theorem 1.4.** We have \( \alpha_- < 1 \). Moreover, for every \( \alpha \in (\alpha_-, 1) \) there exists a Borel dense subset \( A \) of \( J(G) \) with \( \dim_H(A) > 0 \) such that for every non-trivial \( C \in \mathcal{C} \) and for every \( z \in A \), we have \( \text{Hö}(C, z) = \alpha < 1 \) and \( C \) is not differentiable at \( z \).

The proof of Theorem 1.4 will be postponed to Section 7. In the proof, we combine the result that \( C_0 \) is \( \alpha_- \)-Hölder continuous on \( \mathring{C} \) (Theorem 1.3), the multifractal analysis on the pointwise Hölder exponents of \( C_0 \) (Theorems 1.2 and 6.1), an argument on Lipschitz functions on \( \mathring{C} \) and the fact that \( \dim_H(J(G)) < 2 \), which follows from our assumptions (1) and (2) ([Sum98]).

To state Theorem 1.5, let \( M : C(\mathring{C}) \to C(\mathring{C}) \) be the transition operator of the system which is defined by \( M(\phi)(z) = \sum_{j=1}^{+1} p_j \phi(f_j(z)) \), where \( \phi \in C(\mathring{C}), z \in \mathring{C} \). Note that \( M(C^α(\mathring{C})) \subset C^α(\mathring{C}) \) for any \( \alpha \in (0, 1] \).

**Theorem 1.5.** Let \( \alpha \in (\alpha_-, 1) \) and let \( \phi \in C^α(\mathring{C}) \). Then for every minimal set \( L' \) of \( G \) with \( L' \neq L \) we have \( \|M^n(\phi)\|_α \to \infty \) as \( n \to \infty \). In particular, for every \( \xi \in C^α(\mathring{C}) \), we have \( \|M^n(\xi)\|_α \to \infty \) as \( n \to \infty \).

**Proof.** Recall from [Sum11a] that \( C_0 = \lim_{n \to \infty} M^n(\phi) \) in \( C(\mathring{C}) \). Suppose for a contradiction that there exist a subsequence \( (n_j) \) and a constant \( K > 0 \) such that \( \|M^{n_j}(\phi) - M^{n_j}(\phi)\|_α \leq Kd(x, y)\alpha \) for all \( j, x, y \).

Letting \( j \to \infty \) we have \( C_0 \in C^α(\mathring{C}) \). But, this would imply that \( \alpha_- \geq \alpha \) which is a contradiction.

We now present the corollaries of our main results. The first one establishes that every non-trivial \( C \in \mathcal{C} \) varies precisely on the Julia set \( J(G) \). This follows immediately from Theorem 1.1 because the right-hand side of (1.1) is always finite ([Sum98, Theorem 2.6], see also Corollary 1.11). This generalises a previous result from [Sum11a] for \( C_0 = T_p \) and a partial result for the higher order partial derivatives from [Sum13].

**Corollary 1.6.** Every non-trivial \( C \in \mathcal{C} \) varies precisely on \( J(G) \), i.e., \( J(G) \) is equal to the set of points \( z_0 \in \mathring{C} \) such that \( C \) is not constant in any neighborhood of \( z_0 \) in \( \mathring{C} \). In particular, the functions \( C_n, n \in \mathbb{N}_0 \), are linearly independent over \( \mathbb{C} \) and \( \mathcal{C} \) has a representation as a direct sum of vector spaces given by

\[
\mathcal{C} = \bigoplus_{n \in \mathbb{N}_0} CC_n.
\]

We remark again that \( 0 < \dim_H(J(G)) < 2 \) ([Sum98]).
By combining Theorem 1.1 with Birkhoff’s ergodic theorem we obtain the following extension of [Sum13, Theorem 3.40 (2)]. Recall that a Borel probability measure $\nu$ on $J(\tilde{f})$ is called $\tilde{f}$-invariant if $\nu(\tilde{f}^{-1}(A)) = \nu(A)$ for every Borel set $A \in J(\tilde{f})$.

**Corollary 1.7.** Let $\nu$ be an $\tilde{f}$-invariant ergodic Borel probability measure on $J(\tilde{f})$. Let $\pi : \mathbb{R}^n \times \tilde{C} \to \tilde{C}$ denote the canonical projection onto $\tilde{C}$. Then there exists a Borel subset $A$ of $J(G)$ with $(\pi_2(\nu))(A) = 1$ such that for every non-trivial $C \in \mathcal{C}$ and for every $z \in A$, we have

$$
\text{Höl}(C, z) = \frac{-\int \log p_{\omega_0} d\nu(\omega, x)}{\int \log \|f_{\omega_0}(x)\| d\nu(\omega, x)} , \quad \text{where } \omega = (\omega_1, \omega_2, \ldots) \in \mathbb{R}^n.
$$

By combining Corollary 1.7 with [Sum11a, Theorem 3.82] in which the potential theory was used, we obtain the following result (Corollary 1.8) on the pointwise Hölder exponents and the non-differentiability of elements of $\mathcal{C}$. To state the result, when $G$ is a polynomial semigroup, we denote by $\mu_p$ the maximal relative entropy measure on $J(\tilde{f})$ for $\tilde{f}$ with respect to $(\sigma, \tilde{p}_p)$ (see [Sum00], [Sum11a, Remark 3.79]). Note that $\mu_p$ is $\tilde{f}$-invariant and ergodic ([Sum00]). Let $\mu_p = \pi_2(\tilde{\nu}_p)$. For any $(\omega, z) \in \mathbb{R}^n \times \tilde{C}$, let $\nu_\omega(z) := \lim_{n \to \infty} (1/\text{deg}(f_\omega(z))) \log^+ |f_\omega(z)|$, where $\log^+ (a) := \max\{\log a, 0\}$ for every $a > 0$. By the argument in [Ses01], we have that $\nu_\omega(y)$ exists for every $(\omega, z) \in \mathbb{R}^n \times \mathcal{C}$, $(\omega, z) \in \mathbb{R}^n \times \mathcal{C} \to \nu_\omega(z)$ is continuous on $\mathbb{R}^n \times \mathcal{C}$, $\nu_\omega$ is subharmonic on $\mathcal{C}$ and $\nu_\omega$ restricted to the intersection of $\mathcal{C}$ and the basin $\Lambda_\omega$ of $\infty$ for $\{f_\omega\}_{n=1}^{\infty}$ is the Green’s function on $\Lambda_\omega$ with pole at $\infty$. Let $\Lambda(\omega) = \sum \nu_\omega(c)$, where $c$ runs over all critical points of $f_\omega$ in $\Lambda_\omega$, counting multiplicities. Note that $\mu_p = \int_{\mathbb{R}^n} d\nu_\omega \tilde{\nu}_p(\omega)$ where $d^\omega = (\sqrt{-1/2\pi})(\mathcal{D} - \partial)(\nu_\omega) = \nu_\omega$ ([Sum11a, Lemma 5.51]), supp $\mu_p = J(G)$ and $\mu_p$ is non-atomic ([Sum00]). Also, we have $\dim_H(\mu_p) = (\sum_{i \in I} \log \deg f_i - \sum_{i \in I} \log p_i)/(\sum_{i \in I} \log \deg f_i + \int_{\mathbb{R}^n} \Lambda(\omega) d\tilde{\nu}_p(\omega)) > 0$ ([Sum11a, Proof of Theorem 3.82]). Here, $\dim_H(\mu_p) := \inf\{\dim_H(A)\}$ where the infimum is taken over all Borel subsets $A$ of $J(G)$ with $\mu_p(A) = 1$.

**Corollary 1.8.** (1) Suppose that $f_1, \ldots, f_{s+1}$ are polynomials. Then there exists a Borel dense subset $A$ of $J(G)$ with $\mu_p(A) = 1$ and $\dim_H(A) \geq (\sum_{i \in I} \log \deg f_i - \sum_{i \in I} \log p_i)/(\sum_{i \in I} \log \deg f_i + \int_{\mathbb{R}^n} \Lambda(\omega) d\tilde{\nu}_p(\omega)) > 0$ such that for every non-trivial $C \in \mathcal{C}$ and for every $z \in A$, we have

$$
\text{Höl}(C, z) = \frac{-\sum_{i \in I} \log p_i}{\sum_{i \in I} \log \deg f_i + \int_{\mathbb{R}^n} \Lambda(\omega) d\tilde{\nu}_p(\omega)}.
$$

(2) Suppose that $f_1, \ldots, f_{s+1}$ are polynomials satisfying at least one of the following conditions:

(a) $\sum_{i \in I} \log (p_i \log f_i) > 0$.

(b) $G = \{f_1, \ldots, f_{s+1}\}$ is postcritically bounded, i.e. $P(G) \setminus \{\infty\}$ is bounded in $\mathbb{C}$.

(c) $s = 1$.

Then there exists a Borel dense subset $A$ of $J(G)$ with $\mu_p(A) = 1$ such that for every non-trivial $C \in \mathcal{C}$ and for every $z \in A$, we have $\text{Höl}(C, z) < 1$. In particular, every non-trivial $C \in \mathcal{C}$ is non-differentiable $\mu_p$-almost everywhere on $J(G)$.

Note that if for every $f_i$ is a polynomial and $P(G) \setminus \{\infty\}$ is bounded in $\mathbb{C}$, then $\Lambda(\omega) = 0$ for every $\omega \in \mathbb{R}^n$, thus Corollary 1.8 implies that there exists a Borel dense subset $A$ of $J(G)$ with

$$
\mu_p(A) = 1, \quad \dim_H(A) \geq \frac{-\sum_{i \in I} \log p_i \log f_i}{\sum_{i \in I} \log \deg(f_i)} > 1
$$

such that for every non-trivial $C \in \mathcal{C}$ and for every point $z \in A$, we have

$$
\text{Höl}(C, z) = \frac{-\sum_{i \in I} \log p_i \log f_i}{\sum_{i \in I} \log \deg(f_i)} < 1.
$$
The following is one of the other important applications of Corollary 1.7. In order to state the result, let $\delta := \dim_H(J(G))$ and let $H^\delta$ denote the $\delta$-dimensional Hausdorff measure on $\tilde{C}$. Note that by [Sum05], we have $0 < H^\delta(J(G)) < \infty$. Let $C(J(G))$ be the space of all continuous $C$-valued functions on $\tilde{C}$ endowed with supremum norm. Let $L : C(J(G)) \to C(J(G))$ be the operator defined by $L(\varphi)(z) = \sum_{i \in I} f_i(z)\varphi(y_i) ||f'_i(y)||^{-\delta}$ where $\varphi \in C(J(G)), z \in J(G)$. By [Sum05] again, we have that $\gamma = \lim_{n \to \infty} L^n(1) \in C(J(G))$ exists, where 1 denotes the constant function on $J(G)$ taking its value 1, the function $\gamma$ is positive on $J(G)$, and there exists an $\bar{f}$-invariant ergodic probability measure $\hat{\nu}$ on $J(\bar{f})$ such that $\pi_\nu(\hat{\nu}) = \gamma H^\delta/J^\delta(J(G))$ and $\supp \pi_\nu(\nu) = J(G)$. By Corollary 1.7 and [Sum11a, Theorem 3.84 (5)], we obtain the following.

**Corollary 1.9.** Under the above notations, there exists a Borel dense subset $A$ of $J(G)$ with $H^\delta(A) = H^\delta(J(G)) > 0$ such that for every non-trivial $C \in C$ and for every $z \in A$, we have

$$\text{Hö}(C, z) = \frac{-\sum_{i \in I} \log p_i \int_{f_{i}^{-1}(J(G))} \gamma(y)dH^\delta(y)}{\sum_{i \in I} \int_{f_{i}^{-1}(J(G))} \gamma(y) \log ||f_i'(y)||dH^\delta(y)}.$$\]

**Remark 1.10.** We remark that a non-trivial $C \in C'$ may possess points of differentiability. In fact, by choosing one of the probability parameters sufficiently small, we can deduce from Corollary 1.9 that for every non-trivial $C \in C'$ and for $H^\delta$-almost every $z \in J(G)$, we have $\text{Hö}(C, z) > 1$, $C$ is differentiable at $z$ and the derivative of $C$ at $z$ is zero. Note that even under the above condition, Theorem 1.4 implies that there exist an $\alpha < 1$ and a dense subset $A$ of $J(G)$ with $\dim_H(A) > 0$ such that for every non-trivial $C \in C$ and for every $z \in A$, we have $\text{Hö}(C, z) = \alpha < 1$ and $C$ is not differentiable at $z$. In particular, in this case, we have $\alpha_- < 1 < \alpha_+$ and we have a different kind of phenomenon regarding the (complex) analogues of the Takagi function, whereas the original Takagi function does not have this property.

We also have the following corollary of Theorem 1.1. To state the result, by [Sum98, Theorem 2.6] there exists $k_0 \in \mathbb{N}$ such that for every $k \geq k_0$ and for every $\omega = (\omega_i)_{i=1}^k \in I^k$, we have $\min_{z \in f_{\omega}^{-1}(J(G))} ||f_{\omega}'(z)|| > 1$, where $f_{\omega} = f_{\omega_1} \circ \cdots \circ f_{\omega_k}$. Let $p_{\omega} := p_{\omega_1} \cdots p_{\omega_k}$ for $\omega = (\omega_i)_{i=1}^k \in I^k$.

**Corollary 1.11.** For every $k \geq k_0$, we have

$$0 < \min_{\omega \in I^k} \log p_{\omega} \leq \frac{-\log p_{\omega}}{\log \max_{\omega \in I^k} \frac{1}{||f_{\omega}'(z)||}} \leq \alpha_- \leq \frac{-\log p_{\omega}}{\log \min_{\omega \in I^k} \frac{1}{||f_{\omega}'(z)||}} < \infty.$$\]

In particular, if $p_{\min} \min_{\omega \in I^k} ||f_{\omega}'(z)|| > 1$ for every $z \in J(G)$, then for every non-trivial $C \in C'$ and for every $z \in J(G)$, we have that $\text{Hö}(C, z) \leq \alpha_- < 1$ and $C$ is not differentiable at $z$.

**Remark 1.12.** Under assumptions (1)(2)(3), suppose that the maps $f_i, i \in I$, are polynomials. Then $J(G) \subset \mathbb{C}$. Since the spherical metric and the Euclidean metric are equivalent on $J(G)$, it follows that we can replace $|| \cdot ||$ in the definition of $\varphi$, Corollaries 1.7, 1.9, 1.11 by the modulus $| \cdot |$.

**Remark 1.13.** The function $C_0 = T_p$ is continuous (in fact, it is Hölder continuous) on $\tilde{C}$ and varies precisely on the Julia set $J(G)$. Note that by assumptions (1)(2) and [Sum98], we have that $J(G)$ is a fractal set with $0 < \dim_H(J(G)) < 2$. The function $C_0$ can be interpreted as a complex analogue of the devil’s staircase and Lebesgue’s singular functions (Sum11a). In fact, the devil’s staircase is equal to the restriction to $[0, 1]$ of the function of probability of tending to $+\infty$ when we consider random dynamical system on $\mathbb{R}$ such that at every step we choose $f_1(x) = 3x$ with probability $1/2$ and we choose $f_2(x) = 3x - 2$ with probability $1/2$. Similarly, Lebesgue’s singular function $L_p$ with respect to the parameter $p \in (0, 1)$, $p \neq 1/2$ is equal to the restriction to $[0, 1]$ of the function of probability of tending to $+\infty$ when we consider random dynamical system on $\mathbb{R}$ such that at every step we choose $g_1(x) = 2x$ with probability $p$ and we
choose \( g_2(x) = 2x - 1 \) with probability \( 1 - p \). Note that these are new interpretations of the devil’s staircase and Lebesgue’s singular functions obtained in [Sum11a] by the second author of this paper. Similarly, it was pointed out by him that the distributional functions of self-similar measures of IFSs of orientation-preserving contracting diffeomorphisms \( h_i \) on \( \mathbb{R} \) can be interpreted as the functions of probability of tending to \( +\infty \) regarding the random dynamical systems generated by \( (h_i^{-1}) \) ([Sum11a]). From the above point of view, when \( G \) is a polynomial semigroup and \( L = \{ \infty \} \), we call \( C_0 = T_p \) a devil’s coliseum ([Sum11a]). It is well-known ([YHK97]) that the function \( \frac{1}{2} \frac{\partial L_p(x)}{\partial p} |_{p=1/2} \) on \([0,1]\) is equal to the Takagi function \( \Phi(x) = \sum_{m=0}^{\infty} \frac{1}{2^m} \min_{e \in \mathbb{Z}} |2^m x - m| \) (also referred to as the Blancmange function), which is a famous example of a continuous but nowhere differentiable function on \([0,1]\). From this point of view, the first derivatives \( C \in \mathcal{C} \) can be interpreted as complex analogues of the Takagi function. The devil’s staircase, Lebesgue’s singular functions, the Takagi function and the similar functions have been investigated so long in fractal geometry and the related fields. In fact, the graphs of these functions have certain kind of self-similarities and these functions have many interesting and deep properties. There are many interesting studies about the original Takagi function and its related topics ([AK11]). In [AK06], many interesting results (e.g. continuity and non-differentiability, Hölder order, the Hausdorff dimension of the graph, the set of points where the functions take on their absolute maximum and minimum values) of the higher order partial derivatives \( \frac{\partial^n L_p(x)}{\partial p^n} |_{p=1/2} \) of \( L_p(x) \) with respect to \( p \) are obtained. The first study of the complex analogues of the Takagi function was given by the second author in [Sum13]. In particular, some partial results on the pointwise Hölder exponents of them were obtained ([Sum13, Theorem 3.40]). However, it had been an open problem whether the complex analogues of the Takagi function vary precisely on the Julia set or not, until this paper was written. The results of this paper greatly improve the above results from [Sum13].

**Remark 1.14.** The results on the classical Takagi function on \([0,1]\) give some evidence that the results stated in Theorem 1.3 are sharp. Indeed, let us consider the function \( L_{1/2} \) and \( \phi_n(x) = \frac{\partial^n L_p(x)}{\partial p^n} |_{p=1/2} \) for \( n \geq 1 \). Note that \( \frac{1}{2} \phi_1 \) is equal to the original Takagi function. Since we have \( L_{1/2}|_{[0,1]}(x) = x \), \( L_{1/2}|_{[-\infty,0]}(x) = 0 \) and \( L_{1/2}|_{[1,\infty]}(x) = 1 \), the function \( L_{1/2} \) is 1-Hölder (Lipschitz). However, in [AK06] it is shown that the functions \( \phi_n \) on \([0,1]\) are \( a \)-Hölder for every \( a < 1 \), but not 1-Hölder continuous. It would be interesting to further investigate this phenomenon for the complex analogues of the Takagi function.

**Remark 1.15.** We endow \( \text{Rat} \) with the topology induced from the distance \( \text{dist}_{\text{Rat}}(f,g) := \sup_{z \in \mathbb{C}} d(f(z),g(z)) \). Then by [Sum97, Theorem 2.4.1], the fact \( J(G) = \cup_{i \in I} f_i^{-1}(J(G)) \) ([Sum97, Lemma 1.1.4]), [Sum11a, Remark 3.64], and [Sum13, Theorem 3.24]), we have that the set

\[
\{(f_i)_{i \in I} \in (\text{Rat})^I : \deg(f_i) \geq 2 \ (i \in I) \text{ and the conditions (1)(2)(3) hold for } (f_i)_{i \in I}\}
\]

is open in \((\text{Rat})^I\). Also, we have plenty of examples to which we can apply the main results of this paper. See Section 2.

**Remark 1.16.** We remark that by using the method in this paper, we can show similar results to those of this paper for random dynamical systems of diffeomorphisms on \( \mathbb{R} \) (or \( \mathbb{R} \cup \{ \pm \infty \} \)). Note that the case of the classical Takagi function \( \Phi \) corresponds to the degenerated case \( \alpha_- = \alpha_+ \) in Theorem 1.2, though in the case of \( \Phi \) we have the open set condition but do not have the separating condition. We emphasize that in this paper we also deal with the non-degenerated case, which seems generic.

**Remark 1.17.** We remark that under assumptions (1)(2)(3), the iteration of the transition operator \( M \) on some \( C^\alpha(\mathbb{C}) \) is well-behaved (e.g., there exists an \( M \)-invariant finite-dimensional subspace \( U \) of \( C^\alpha(\mathbb{C}) \)
such that for every $h \in C^0(\hat{\mathbb{C}})$, $M^n(h)$ tends to $U$ as $n \to \infty$ exponentially fast) and $M$ has a spectral gap on $C^0(\hat{\mathbb{C}})$ ([Sum97, Lemma 1.1.4(2)], [Sum11a, Propositions 3.63, 3.65], [Sum13, Theorems 3.30, 3.31]). Note that this is a randomness-induced phenomenon (new phenomenon) in random dynamical systems which cannot hold in the deterministic iteration dynamics of rational maps of degree two or more, since for every $f \in \text{Rat}$ with $\deg(f) \geq 2$, the dynamics of $f$ on $J(f)$ is chaotic. Combining the above spectral gap property of $M$ on $C^0(\hat{\mathbb{C}})$ and the perturbation theory for linear operators ([Kato80]) implies that the map $x = (x_1, \ldots, x_n) \mapsto T_G(x_1, \ldots, x_n) \in C^0(\hat{\mathbb{C}})$ is real-analytic in a neighbourhood of $p$ in the space $W := \{(q_i)_{i=1}^n \in (0,1) : \sum_{i=1}^n q_i < 1\}$ ([Sum13, Theorem 3.32]). Thus it is very natural and important for the study of the random dynamical system to consider the higher order partial derivatives of $T_p$ with respect to the probability vectors. Moreover, it is very interesting that $C_n$ is a solution of the functional equation $(Id - M)(C_n) = F$, where $F$ is a function associated with lower order partial derivatives of $T_p$ (Lemma 4.1). In fact, by using the spectral gap properties of $M$ on $C^0(\hat{\mathbb{C}})$ and the arguments in the proof of [Sum13, Theorem 3.32], for any $n \in \mathbb{N} \setminus \{0\}$, we can show that (I) $C_n$ is the unique continuous solution of the above functional equation under the boundary condition $C_n|_{\partial \mathbb{C}} = 0$ and (II) $C_n = \sum_{j=0}^n M^j(F)$ in $C^0(\hat{\mathbb{C}})$ and in $C^0(\hat{\mathbb{C}})$ for small $\alpha > 0$. Thus, we have a system of functional equations for elements $C_n$ (see Lemma 4.1). Note that this is the first paper to investigate the pointwise Hölder exponents and other properties of the higher order partial derivatives $C_n$ of the functions $T_p$ of probability of tending to minimal sets with respect to the probability parameters regarding random dynamical systems which have several variables of probability parameters. This is a completely new concept. In fact, even in the real line, there has been no study regarding the objects similar to the above. Even more, in this paper we deal with the complex linear combinations of partial derivatives $C_n$, which are of course completely new objects in mathematics coming naturally from the study of random dynamical systems and fractal geometry. We also remark that the original Takagi function is associated with Lebesgue’s singular functions, but there has been no study about the higher order partial derivatives of the distribution functions of singular measures with respect to the parameters.

The key in the proof of the main results of this paper is to consider the system of functional equations satisfied by the elements of $\mathcal{C}$ (Lemma 4.1). The composition of these equations along orbits is best described in terms of an associated matrix cocycle $A(\omega, k)$. By using combinatorial arguments, we show a formula for the components of the matrix $A(\omega, k)$, and we carefully estimate the polynomial growth order of these components, as $k$ tends to infinity (Lemma 4.8). Combining this with some calculations of the determinants of matrices which are similar to the Vandermonde determinant (Lemma 4.10), we deduce the linear independence of the vectors $(C_r(a) - C_r(b))_{a,b \in \mathbb{C}}$ for certain points $a, b \in J(G)$ which are close to a given point $x_0 \in J(G)$ (Proposition 4.11). Here, $r \leq n$ means that $r_i \leq n_i$ for each $i$. From the linear independence of these vectors we deduce that a certain linear combination of vectors $(C_r(a) - C_r(b))_{r \leq n}$ is bounded away from zero (Lemma 5.2). This gives us the upper bound of the pointwise Hölder exponents of $C \in \mathcal{C}$. Note that this argument is the key to prove Theorem 1.1 and it is the crucial point to derive that the elements $C \in \mathcal{C}$ are not locally constant in any point of the Julia set (Corollary 1.6). We emphasize that those ideas are very new and they give us strong and systematic tools to analyze random dynamical systems, singular functions, fractal functions and other related topics.

In Section 2, we give plenty of examples which illustrate the main results of this paper. In Section 3 we give some fundamental tools of rational semigroups and random complex dynamics. In Section 4 we describe the system of functional equations for the elements of $\mathcal{C}$ and we estimate the growth order of components of associated matrix cocycles. In Section 5, we give the proof of Theorem 1.1, by using the results from Section 4. In Section 6, we present the detailed version Theorem 6.1 of Theorem 1.2 and we
give the proof of it by using Theorem 1.1 and some results from [JS15a, Theorem 1.2]. Also, we give the proof of Theorem 1.3 by using the argument in the proof of Theorem 1.1 and by developing some ideas from [KS08, JKP09]. In Section 7, we give the proof of Theorem 1.4 by combining that \( C_0 \) is \( \alpha - \) Hölder continuous on \( \hat{C} \) (Theorem 1.3), the multifractal analysis on the pointwise Hölder exponents of \( C_0 \) (Theorems 1.2 and 6.1), an argument on the Lipschitz functions on \( \hat{C} \) and the result \( 0 < \dim_H(J(G)) < 2 \), which follows from the assumptions (1) and (2) ([Sum98]).

2. Examples

In this section, we give some examples which illustrate the main results of this paper.

For \( f \in \text{Rat} \), we set \( F(f) := F((f)), J(f) := J((f)) \), and \( P(f) = P((f)) \). We denote by \( \mathcal{P} \) the set of polynomials of degree two or more. For \( g \in \mathcal{P} \), we denote by \( K(g) \) the filled-in Julia set. If \( G \) is a rational semigroup and if \( K \) is a non-empty compact subset of \( \hat{C} \) such that \( g(K) \subset K \) for each \( g \in G \), then Zorn’s lemma implies that there exists a minimal set \( L \) of \( G \) with \( L \subset K \) ([Sum11a, Remark 3.9]).

The following propositions show us several methods to produce many examples of \((f_1, \ldots, f_{s+1}) \in (\text{Rat})^{s+1}\) which satisfy assumptions (1)(2)(3) of this paper. For such elements \((f_1, \ldots, f_{s+1})\) and for every \( p = (p_i)_{i=1}^s \in (0,1)^s \) with \( \sum_{i=1}^s p_i < 1 \), we can apply the results Theorems 1.1, 1.2, 1.3, 1.4, 1.5 and Corollaries 1.6, 1.7, 1.9 and 1.11 in Section 1.

**Proposition 2.1.** Let \((g_1, \ldots, g_{s+1}) \in (\text{Rat})^{s+1} \) with \( \deg(g_i) \geq 2 \), \( i = 1, \ldots, s+1 \). Suppose that \((g_1, \ldots, g_{s+1}) \) is hyperbolic, \( J(g_i) \cap J(g_j) = \emptyset \) for every \((i, j) \) with \( i \neq j \), and that there exist at least two distinct minimal sets of \((g_1, \ldots, g_{s+1})\). Then there exists \( m \in \mathbb{N} \) such that for every \( n \in \mathbb{N} \) with \( n \geq m \), setting \( f_i = g_i^n, i = 1, \ldots, s+1 \), the element \((f_1, \ldots, f_{s+1})\) satisfies assumptions (1)(2)(3) of this paper.

**Proof.** Let \( H = (g_1, \ldots, g_{s+1}) \). Since \( J(g_i), i = 1, \ldots, s+1 \) are mutually disjoint and since attracting cycles of \( g_i \) are included in \( F(H) = \hat{C} \setminus J(H) \), there exists \( m \in \mathbb{N} \) such that for every \( n \geq m \), setting \( f_i = g_i^n, i = 1, \ldots, \), the sets \( f_i^{-1}(J(H)), i = 1, \ldots, s+1 \), are mutually disjoint. Let \( G = (f_1, \ldots, f_{s+1}) \). Then \( G \) is a subsemigroup of \( H \). Thus \( F(H) \subset F(G) \) and \( P(G) \subset P(H) \). Hence \( P(G) \subset P(H) \subset F(H) \subset F(G) \). Therefore \( H \) is hyperbolic. Moreover, since \( J(G) \subset J(H) \), the sets \( f_i^{-1}(J(G)), i = 1, \ldots, s+1 \), are mutually disjoint. Let \( L_1 \) and \( L_2 \) be two distinct minimal sets of \( H \). Then for every \( g \in H \) and for every \( i = 1, 2 \), we have \( g(L_i) \subset L_i \). In particular, for every \( f \in G \) and for every \( i = 1, 2, f(L_i) \subset L_i \). By [Sum11a, Remark 3.9] it follows that for every \( i = 1, 2 \), there exists a minimal set \( L_i' \) of \( G \) with \( L_i' \subset L_i \). Hence \((f_1, \ldots, f_{s+1})\) satisfies assumptions (1)(2)(3) of this paper.

**Proposition 2.2.** Let \((g_1, \ldots, g_{s+1}) \in (\text{Rat})^{s+1} \) with \( \deg(g_i) \geq 2 \), \( i = 1, \ldots, s+1 \). Suppose that \( \cup_{i=1}^{s+1} P(g_i) \subset \cap_{i=1}^{s+1} F(g_i), \text{that } J(g_i) \cap J(g_j) = \emptyset \) for every \((i, j) \) with \( i \neq j \), and that there exist two compact subsets \( K_1, K_2 \) of \( \hat{C} \) with \( K_1 \cap K_2 = \emptyset \) such that \( g_i(K_j) \subset K_j \) for every \( i = 1, \ldots, s+1 \) and for \( j = 1, 2 \). Then there exists \( m \in \mathbb{N} \) such that for every \( n \in \mathbb{N} \) with \( n \geq m \), setting \( f_i = g_i^n, i = 1, \ldots, s+1 \), the element \((f_1, \ldots, f_{s+1})\) satisfies assumptions (1)(2)(3) of this paper.

**Proof.** Let \( \varepsilon > 0 \) be so small that \( B(\cup_{i=1}^{s+1} P(g_i), 2\varepsilon) \subset \cap_{i=1}^{s+1} F(g_i) \) and \( B(J(g_j), 2\varepsilon) \cap B(J(g_i), 2\varepsilon) = \emptyset \) for every \((i, j) \) with \( i \neq j \). Let \( m \in \mathbb{N} \) be a sufficiently large number. Let \( n \geq m \) and let \( f_i = g_i^n \). Let \( G = (f_1, \ldots, f_{s+1}) \). Let \( A_k := B(\cup_{i=1}^{s+1} P(g_i), ke) \) for each \( k = 1, 2 \). Then taking \( m \) so large, we have \( f_i(A_k) \subset A_k \) for every \( i = 1, \ldots, s+1 \). It implies \( P(G) \subset \bigcup_{j=1}^{s+1} A_j \subset A_2 \subset F(G) \). Hence \( G \) is hyperbolic. Moreover, by [Sum11a, Remark 3.9], there exists a minimal set \( L_j \) of \( G \) with \( L_j \subset K_j \) for every \( j = 1, 2 \). By Proposition 2.1, the statement of our proposition holds.
Combining [Sum11a, Remark 3.9] with [Sum11a, Proposition 6.1], we also obtain the following.

**Proposition 2.3.** Let $f_1 \in \mathcal{P}$ be hyperbolic, i.e., $P(f_1) \subset F(f_1)$. Suppose that $\text{Int}(K(f_1)) \neq \emptyset$, where $\text{Int}$ denotes the set of interior points. Let $b \in \text{Int}(K(f_1))$ be a point. Let $d \in \mathbb{N}$ with $d \geq 2$. Suppose that $(\deg(f_1), d) \neq (2, 2)$. Then there exists a number $c > 0$ such that for each $\lambda \in \{ \lambda \in \mathbb{C} : 0 < |\lambda| < c \}$, setting $f_{2, \lambda}(z) := \lambda(z - b)^d + b$, we have the following.

1. $(f_1, f_{2, \lambda})$ satisfies assumptions (1)(2)(3) of this paper with $s = 1$.
2. If $J(f_1)$ is connected, then $P((f_1, f_{2, \lambda})) \setminus \{ \infty \}$ is bounded in $\mathbb{C}$.

Thus combining the above with Remark 1.15, we obtain that for any $(f_1, f_{2, \lambda})$ in the above, there exists a neighborhood $V$ of $(f_1, f_{2, \lambda})$ in $(\text{Rat})^2$ such that for every $(g_1, g_2) \in V$, assumptions (1)(2)(3) of this paper are satisfied and Theorems 1.1, 1.2, 1.3, 1.4, 1.5 and Corollaries 1.6, 1.7, 1.9 and 1.11 in Section 1 hold. Also, endowing $\mathcal{P}$ with the relative topology from Rat, we have that there exists an open neighborhood $W$ of $(f_1, f_{2, \lambda})$ in $(\mathcal{P})^2$ such that for every $(g_1, g_2) \in W$ and for every $p = p_1 \in (0, 1)$, Corollary 1.8 holds.

**Example 2.4.** Let $(f_1, f_2) \in \mathcal{P}^2$ be an element such that $\langle f_1, f_2 \rangle$ is hyperbolic, $P((f_1, f_2)) \setminus \{ \infty \}$ is bounded in $\mathbb{C}$ and $J((f_1, f_2))$ is disconnected. Note that there are plenty of examples of such elements $(f_1, f_2)$ (Proposition 2.3, [Sum11b, Sum15b]). Then by [Sum09, Theorems 1.5, 1.7], we have that $f_1^{-1}(J(G)) \cap f_2^{-1}(J(G)) = \emptyset$ where $G = (f_1, f_2)$. Thus $(f_1, f_2)$ satisfies assumptions (1)(2)(3) of this paper with $s = 1$ and all results in Section 1 hold for $(f_1, f_2)$ and for every $p = p_1 \in (0, 1)$.

**Example 2.5.** Let $g_1(z) = z^2 - 1, g_2(z) = z^2/4$, and let $g_i = g_i \circ g_i$, $i = 1, 2$. Let $G = (f_1, f_2)$. Then $(f_1, f_2)$ satisfies the assumptions (1)(2)(3) of this paper with $s = 1$ and $P(G) \setminus \{ \infty \}$ is bounded in $\mathbb{C}$ ([Sum11a, Example 6.2],[Sum13, Example 6.2]). Thus for this $(f_1, f_2)$, all results of Section 1 hold. In particular, every non-trivial $C \subset \mathcal{C}$ is Hölder continuous on $\hat{\mathbb{C}}$ and varies precisely on the Julia set $J(G)$ (Corollary 1.6). Moreover, by Corollary 1.8, there exists a Borel dense subset $A$ of $J(G)$ with $\mu_p(A) = 1$, $\dim_H(A) \geq \dim_H(\mu_p) = \frac{3}{2}$ such that for every non-trivial $C \subset \mathcal{C}$ and for every $z \in A$, we have $\alpha_{-} \leq \text{Hö}l(C, z) = \frac{1}{2} \leq \alpha_{+}$ and $C$ is not differentiable at $z$. For the figures of $J(G)$ and the graphs of $C_0, C_1$ with $L = \{ \infty \}$, see [Sum13, Figures 2,3,4]. Note that Theorem 1.2 implies that $\alpha_{-} < \alpha_{+}$ for every probability vector (parameter) $p' \in (0, 1)$.

**Example 2.6.** Let $\lambda \in \mathbb{C}$ with $0 < |\lambda| \leq 0.01$ and let $f_1(z) = z^2 - 1, f_2(z) = \lambda z^3$. Then by [Sum15a, Example 5.4], the element $(f_1, f_2)$ satisfies assumptions (1)(2)(3) of this paper with $s = 1$ and $P((f_1, f_2)) \setminus \{ \infty \}$ is bounded in $\mathbb{C}$. Thus all results in Section 1 hold for $(f_1, f_2)$ and for every probability vector (parameter) $p = p_1 \in (0, 1)$. Thus, setting $p_1 = \frac{1}{2}$, $G = (f_1, f_2)$ and $L = \{ \infty \}$, every non-trivial $C \subset \mathcal{C}$ is Hölder continuous on $\hat{\mathbb{C}}$ and varies precisely on $G$, and Corollary 1.8 implies that there exists a Borel dense subset $A$ of $J(G)$ with $\mu_p(A) = 1$ and $\dim_H(A) \geq 1 + \frac{2 \log 2}{2 \log 2 + \log 3} \approx 1.7737$ such that for every non-trivial $C \subset \mathcal{C}$ and for every $z \in A$, we have $\alpha_{-} \leq \text{Hö}l(C, z) = \frac{2 \log 2}{2 \log 2 + \log 3} (\approx 0.7737) \leq \alpha_{+}$ and $C$ is not differentiable at $z$. Also, by Theorem 1.2, we have $\alpha_{-} < \alpha_{+}$ for every $p' \in (0, 1)$.

**Example 2.7.** Let $g_1, g_2 \in \mathcal{P}$ be hyperbolic. Suppose that $(J(g_1) \cup J(g_2)) \cap (P(g_1) \cup P(g_2)) = \emptyset$, $K(g_1) \subset \text{Int}(K(g_2))$, and the union of attracting cycles of $g_2$ in $\mathbb{C}$ is included in $\text{Int}(K(g_1))$. Then by [Sum11a, Proposition 6.3], there exists an $m \in \mathbb{N}$ such that for each $n \in \mathbb{N}$ with $n \geq m$, setting $f_1 = g_1^m, f_2 = g_2^m$, we have that $(f_1, f_2)$ satisfies assumptions (1)(2)(3) of this paper with $s = 1$. Thus all statements of the results in Section 1 hold for $(f_1, f_2)$ and for every $p = p_1 \in (0, 1)$.

The following proposition provides us a method to construct examples of $(f_1, \ldots, f_{s+1}) \in (\mathcal{P}^{s+1})$ for which (1)(2)(3) hold and $P((f_1, \ldots, f_{s+1})) \setminus \{ \infty \}$ is bounded in $\mathbb{C}$. For such elements $(f_1, \ldots, f_{s+1})$ and for every $p \in (0, 1)^{s+1}$ with $\sum_{i=1}^{s+1} p_i < 1$, we can apply all the results in Section 1.
Proposition 2.8. Let $g_1,\ldots, g_{s+1} \in \mathcal{P}$ be hyperbolic and suppose that $J(f_i)$ is connected for every $i = 1,\ldots, s+1$. Suppose that $J(f_i) \subset \text{Int}(K(f_{s+1}))$ for every $i = 1,\ldots, s$. Suppose also that $\bigcup_{i=1}^{s+1} P(g_i) \setminus \{\infty\} \subset \text{Int}(K(f_1))$. Then there exists an $m \in \mathbb{N}$ such that for every $n \in \mathbb{N}$ with $n \geq m$, setting $f_i = g_i^n, i = 1,\ldots, s+1$, the element $(f_1,\ldots, f_{s+1})$ satisfies assumptions (1)(2)(3) and $P((f_1,\ldots, f_{s+1})) \setminus \{\infty\}$ is bounded in $\mathbb{C}$.

Proof. Let $n \in \mathbb{N}$ be large enough and let $f_i = g_i^n$. Then there exists a compact subset $A$ of $\text{Int}(K(f_1))$ such that $\bigcup_{i=1}^{s+1} f_i(K(f_1)) \subset A$. Also, $\bigcup_{i=1}^{s+1} f_i(A \cup P(f_1) \setminus \{\infty\}) \subset \text{Int}(K(f_1))$. Hence $P(g) \setminus \{\infty\} \subset \text{Int}(K(f_1))$, where $G = \langle f_1,\ldots, f_{s+1} \rangle$. In particular, $P(g) \setminus \{\infty\}$ is bounded in $\mathbb{C}$. Since $\bigcup_{i=1}^{s+1} f_i(K(f_1)) \subset K(f_1)$, we obtain that $\text{Int}(K(f_1)) \subset F(G)$. Hence, $P(g) \subset F(G)$ and $G$ is hyperbolic. Let $B = K(g_{s+1}) \cap \text{Int}(K(f_1))$.

By taking $n$ large enough, we may assume that $\bigcup_{i=1}^{s+1} f_i^{-1}(B) \subset B$ and the sets $f_i^{-1}(B), i = 1,\ldots, s+1$, are mutually disjoint. Since $\bigcup_{i=1}^{s+1} f_i^{-1}(B) \subset B$, [HM96, Corollary 3.2] implies that $J(G) \subset B$. Hence, the sets $f_i^{-1}(J(G)), i = 1,\ldots, s+1$, are mutually disjoint. Since $\bigcup_{i=1}^{s+1} f_i(K(f_1)) \subset K(f_1)$, [Sum11a, Remark 3.9] implies that there exists a minimal set $L$ of $G$ with $L \subset K(f_1)$. Thus, there exist at least two minimal sets of $G$. Hence, $(f_1,\ldots, f_{s+1})$ satisfies assumptions (1)(2)(3) of our paper and $P(g) \setminus \{\infty\}$ is bounded in $\mathbb{C}$.

Example 2.9. Let $g_1(z) = z^2 - 1$ and let $g_2(z) = \frac{1}{1+z^2}, i = 2,\ldots, s+1$. Then $(g_1,\ldots, g_{s+1})$ satisfies the assumptions of Proposition 2.8. Note that $z^2 - 1$ can be replaced by any hyperbolic element $f \in \mathcal{P}$ with connected Julia set such that $J(f) \subset \{z \in \mathbb{C} : |z| < 10\}$ and $0 \in \text{Int}(K(f))$.

From one element $(g_1,\ldots, g_m) \in (\text{Rat})^m$ which satisfies assumptions (1)(2)(3) with $s+1 = m$, we obtain many elements which satisfy assumptions (1)(2)(3) of our paper as follows.

Proposition 2.10. Let $(g_1,\ldots, g_m) \in (\text{Rat})^m$ with $\deg(g_i) \geq 2, i = 1,\ldots, m$, and suppose that $(g_1,\ldots, g_m)$ satisfies assumptions (1)(2)(3) of this paper. Let $n \in \mathbb{N}$ with $n \geq 2$ and let $f_1,\ldots, f_{s+1}$ be mutually distinct elements of $\{g_0, \circ \cdots \circ g_0 | \{0_1,\ldots, 0_m\} \in \{1,\ldots, m\}^s\}$ where $s \geq 1$. Then we have the following.

(I) $(f_1,\ldots, f_{s+1})$ satisfies assumptions (1)(2)(3) of this paper. Thus all statements in Theorems 1.1, 1.2, 1.3, 1.4, 1.5 and Corollaries 1.6, 1.7, 1.9 and 1.11 in Section 1 hold for $(f_1,\ldots, f_{s+1})$, for every minimal set $L$ of $(f_1,\ldots, f_{s+1})$ and for every $p = (p_1,\ldots, p_s) \in \{0,1\}^s$ with $\sum_{i=1}^s p_i < 1$.

(II) If, in addition to the assumption, $(f_1,\ldots, f_{s+1}) \in \mathcal{P}^{\infty}$, then statement (1) in Corollary 1.8 holds for $(f_1,\ldots, f_{s+1})$ and for every $p$, and statement (2) in Corollary 1.8 holds for $(f_1,\ldots, f_{s+1})$ and for every $p$ provided that one of (a)(b)(c) in the assumption of Corollary 1.8 (2) holds.

(III) If, in addition to the assumption of our proposition, $(g_1,\ldots, g_m) \in \mathcal{P}^m$ and $P((g_1,\ldots, g_m)) \setminus \{\infty\}$ is bounded in $\mathbb{C}$, then $P((f_1,\ldots, f_{s+1})) \setminus \{\infty\}$ is bounded in $\mathbb{C}$. Thus, statement (2) in Corollary 1.8 holds for $(f_1,\ldots, f_{s+1})$ and for every $p$.

Proof. Let $H = \langle g_1,\ldots, g_m \rangle$ and let $G = \langle f_1,\ldots, f_{s+1} \rangle$. Then $G$ is a subsemigroup of $H$. Hence, $F(H) \subset F(G)$ and $P(G) \subset P(H)$. Since $H$ is hyperbolic, we have $P(G) \subset P(H) \subset F(H) \subset F(G)$. Thus, $G$ is hyperbolic. Hence, $(f_1,\ldots, f_{s+1})$ satisfies assumption (1) of our paper. Since the sets $g^{-1}(J(H)): i = 1,\ldots, m$, are mutually disjoint, we have that the sets $(g_0,\circ \cdots \circ g_0)^{-1}(J(H)), (0_1,\ldots, 0_m) \in \{1,\ldots, m\}^s$, are mutually disjoint. Since $J(G) \subset J(H)$, it follows that the sets $f_i^{-1}(J(G)), i = 1,\ldots, s+1$, are mutually disjoint. Hence $(f_1,\ldots, f_{s+1})$ satisfies assumption (2) of our paper. Since $(g_1,\ldots, g_m)$ satisfies assumption (3) of our paper, there exist at least two distinct minimal sets $L_1$ and $L_2$ of $(g_1,\ldots, g_m)$. Therefore for every $g \in \langle g_1,\ldots, g_m \rangle$ and for every $i = 1,2$, we have $g(L_i) \subset L_i$. In particular, for every $f \in (f_1,\ldots, f_{s+1}), f(L_i) \subset L_i$. By [Sum11a, Remark 3.9] it follows that for every $i = 1,2$, there exists a minimal set $L_i' \subset (f_1,\ldots, f_{s+1})$. Hence, $(f_1,\ldots, f_{s+1})$ satisfies assumption (3) of our paper. If, in addition to the assumption of our proposition, $(g_1,\ldots, g_m) \in \mathcal{P}^m$ and $P(H) \setminus \{\infty\}$ is bounded in $\mathbb{C}$, then since $P(G) \setminus \{\infty\} \subset P(H) \setminus \{\infty\}$, we obtain that $P(G) \setminus \{\infty\}$ is bounded in $\mathbb{C}$. □
Regarding Remark 1.15, we also have the following.

**Lemma 2.11.** Let \( s \geq 1 \) and let \( I = \{1, \ldots, s + 1\} \). Then the set

\[
\{(f_i)_{i \in I} \in \mathcal{P}^I : (f_i)_{i \in I} \text{ satisfies assumptions (1)(2)(3) and } P((f_1, \ldots, f_{s+1})) \setminus \{\infty\} \text{ is bounded in } \mathbb{C}\}
\]

is open in \( \mathcal{P}^I \).

**Proof.** By [Sum10, Lemma 5.4], we have that the set of elements \((f_i)_{i \in I} \in \mathcal{P}^I\) for which assumption (1) holds and \(P((f_1, \ldots, f_{s+1})) \setminus \{\infty\}\) is bounded is open in \( \mathcal{P}^I \). Combining this with Remark 1.15, we see that the statement of our lemma holds.

We remark that the above examples, propositions and lemma in this section and Remark 1.15 imply that we have plenty of examples to which we can apply the results in Section 1.

We give examples to which we can apply Corollary 1.11.

**Lemma 2.12.** Let \((g_1, \ldots, g_{s+1})\) be an element which satisfies assumptions (1)(2)(3). Let \( p = (p_i)_{i=1}^s \in (0,1)^s \) with \( \sum_{i=1}^s p_i < 1 \). Let \( p_{i+1} = 1 - \sum_{i=1}^s p_i \). Then there exists an \( m \in \mathbb{N} \) such that for every \( n \in \mathbb{N} \) with \( n \geq m \), setting \( f_i = g_i, i = 1, \ldots, s+1 \), and setting \( G := (f_1, \ldots, f_{s+1}) \), we have that \((f_1, \ldots, f_{s+1})\) satisfies assumptions (1)(2)(3) and \( p_i \min_{z \in \mathbb{C}} |f_i^{-1}(z)| > 1 \) for every \( i = 1, \ldots, s+1 \). Thus, for every minimal set \( L \) of \((f_1, \ldots, f_{s+1})\), and for every \( z \in J(G) \), we have that every non-trivial \( C \in \mathcal{E} \) satisfies \( \text{Höl}(C,z) \leq \alpha_+ < 1 \) and \( C \) is not differentiable at \( z \).

**Proof.** By Proposition 2.10, there exists an \( m \in \mathbb{N} \) such that for every \( n \in \mathbb{N} \) with \( n \geq m \), setting \( f_i = g_i, i = 1, \ldots, s+1 \), we have that \((f_1, \ldots, f_{s+1})\) satisfies assumptions (1)(2)(3). Since \( H := (g_1, \ldots, g_{s+1}) \) is hyperbolic, the expanding property of \( H \) on \( J(H) \) \((\text{[Sum98, Theorem 2.6]})\) implies that if \( n \) is large enough, then \( p_i \min_{z \in \mathbb{C}} |f_i^{-1}(z)| > 1 \) for every \( i = 1, \ldots, s+1 \), where \( G = (f_1, \ldots, f_{s+1}) \). Combining this with Corollary 1.11, we obtain that, for each minimal set \( L \) of \( G \), and for every \( z \in J(G) \), we have that every non-trivial \( C \in \mathcal{E} \) satisfies \( \text{Höl}(C,z) \leq \alpha_+ < 1 \) and \( C \) is not differentiable at \( z \).

## 3. Preliminaries

In this section, we recall some fundamental facts on rational semigroups and random complex dynamics which are needed in the proofs of the main results of this paper.

Let \( G \) be a rational semigroup and let \( z \in \mathbb{C} \). The backward orbit \( G^{-1}(z) \) of \( z \) and the set of exceptional points \( E(G) \) are defined by \( G^{-1}(z) := \cup_{g \in G} g^{-1}(z) \) and \( E(G) := \{ z \in \mathbb{C} : \text{card}(G^{-1}(z)) < \infty \} \). We say that a set \( A \subset \mathbb{C} \) is \( G \)-backward invariant, if \( g^{-1}(A) \subset A \) for each \( g \in G \), and we say that \( A \) is \( G \)-forward invariant, if \( g(A) \subset A \), for each \( g \in G \).

The following was proved in [HM96] (see also [Sum00, Lemma 2.3], [Sta12]).

**Lemma 3.1.** Let \( G \) be a rational semigroup which has an element of degree two or more. Then we have the following.

(a) \( F(G) \) is \( G \)-forward invariant and \( J(G) \) is \( G \)-backward invariant.
(b) \( J(G) \) is a perfect set,
(c) \( \text{card}(E(G)) \leq 2 \).
(d) If \( z \in \widehat{\mathbb{C}} \setminus E(G) \), then \( J(G) \subset G^{-1}(z) \). In particular, if \( z \in J(G) \setminus E(G) \), then \( G^{-1}(z) = J(G) \).
(e) \( J(G) \) is the smallest closed subset of \( \mathbb{C} \) containing at least three points which is \( G \)-backward invariant.
The following lemma ([Sum97, Lemma 1.1.4]) is easy to see but important.

**Lemma 3.2.** Let $G$ be a rational semigroup generated by $\{f_1, \ldots, f_m\}$. Then $J(G) = \cup_{j=1}^{m} f_j^{-1}(J(G))$.

We remark that by [Sum98] and [Sum05, Remark 5], assumption (1) of this paper is equivalent to the property that the associated skew product map is expanding in the sense of [Sum05] and [JS15a]. Combining assumptions (1)(2) of our paper and [Sum01, Theorem 2.14 (2), Lemma 2.4], we obtain the following.

**Lemma 3.3.** Suppose that $(f_1, \ldots, f_{s+1})$ satisfies assumptions (1)(2) of our paper. Let $G = \langle f_1, \ldots, f_{s+1} \rangle$, let $I = \{1, \ldots, s+1\}$ and let $f$ be the skew product map associated with $(f_1, \ldots, f_{s+1})$. Then $J(f) = \cup_{\omega \in \mathcal{C}} (\omega) \times J_\omega$ and $J(G) = \bigsqcup_{\omega \in \mathcal{C}} J_\omega$, where $\bigsqcup$ denotes the disjoint union. Also, for every $\omega = (\omega_i)_{i \in \mathbb{N}} \in f^I$, we have $f_{\omega_0}(J_{\omega_0}) = J_{\pi(\omega)}$ and $f_{\omega_1}^{-1}(J_{\pi(\omega)}) = J_\omega$. We remark that $\pi \circ f = \sigma \circ \pi$ and $f^{-1}(J(f)) = J(f) = f(J(f))$ ([Sum00]). We also remark that by Zorn’s lemma, there always exists a minimal set of $G$.

For the fundamental tools and recent results of complex dynamics, see [Sum11a, Sum13].

## 4. System of Functional Equations and Estimates

In this section, we describe the system of functional equations for the elements of $\mathcal{C}$ and we estimate the growth order of components of associated matrix cocycles $A(\omega,k)$. More precisely, in Lemma 4.8 we show that every component of $A(\omega,k)$ is of polynomial order with respect to $k$. Also, in some special cases we determine the precise polynomial growth rate.

Let $(f_1, \ldots, f_{s+1}) \in \text{Rat}^{s+1}$ be an element satisfying assumptions (1)(2)(3) of this paper and let $p = (p_i)_{i=1}^s \in (0,1)^s$ with $\sum_{i=1}^s p_i < 1$. Let $p_{s+1} = 1 - \sum_{i=1}^s p_i$. Recall that the transition operator $M : C(\mathcal{C}) \to C(\mathcal{C})$ of the random dynamical system generated by $(f_1, \ldots, f_{s+1})$ and $p$ in Section 1 is defined by $M(h) := \sum_{i=1}^{s+1} p_i \cdot (h \circ f_i) + h \in C(\mathcal{C})$. Recall from [Sum11a] that $M(C_0) = C_0$. Next lemma gives a system of functional equations for the elements of $\mathcal{C}$.

**Lemma 4.1.** For every $n = (n_i)_{i=1}^s \in \mathbb{N}_0^s$ we have

\begin{equation}
C_n = M(C_n) + \sum_{i=1}^s n_i (C_{n-e_i} \circ f_i - C_{n-e_i-e_j} \circ f_{s+1}),
\end{equation}

where $e_i$ denotes the element of $\mathbb{N}_0^s$ such that the $i$-th component is 1 and all the other components are 0.

**Proof.** The proof is by induction on the order $n := |n| \geq 0$. The case $n = 0$ follows because $C_0 = T_p$ is a fixed point of $M$. Now suppose that the lemma holds for derivatives of order $n \geq 0$. Let $j \in \{1, \ldots, s\}$. By taking the partial derivative with respect to $p_j$ on both sides of (4.1) we see that

\begin{align*}
C_{n+e_j} &= M(C_{n+e_j}) + C_n \circ f_j - C_n \circ f_{s+1} + \sum_{i=1}^s n_i (C_{n-e_i+e_j} \circ f_i - C_{n-e_i-e_j} \circ f_{s+1}) \\
&= M(C_{n+e_j}) + (n_j + 1) (C_n \circ f_j - C_n \circ f_{s+1}) + \sum_{i=1,i \neq j}^s n_i (C_{n-e_i+e_j} \circ f_i - C_{n-e_i-e_j} \circ f_{s+1}).
\end{align*}

Hence, the equation (4.1) holds for $n+e_j$ and the lemma follows by induction on $n$. \hfill $\square$

In the following, any element $A \in \mathbb{R}^{\mathbb{N}_0^s \times \mathbb{N}_0^s}$ is represented as $A = (A_{x,y})_{(x,y) \in \mathbb{N}_0^s \times \mathbb{N}_0^s}$, where $A_{x,y} \in \mathbb{R}$, and such an element $A$ is called an $(\mathbb{N}_0^s)$-matrix. $A_{x,y}$ is called the $(x,y)$-component of $A$. 

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Definition 4.2. For $\omega \in I^N$ we define the matrix $A_0(\omega, 1) \in \mathbb{R}^{N_0 \times N_0}$ given by

$$A_0(\omega, 1) := \begin{cases} \sum_{n \in \mathbb{N}_0} (p_{\omega_1} 1_{n, n} + n \omega_1 1_{n, n - e_1}), & \omega_1 \neq s + 1 \\ \sum_{n \in \mathbb{N}_0} (p_{\omega_1} 1_{n, n} - \sum_{i=1}^{s} n_i 1_{n, n - e_i}), & \omega_1 = s + 1, \end{cases}$$

where $1_{n,m} \in \mathbb{R}^{N_0 \times N_0}$ denotes the matrix such that for every $(x, y) \in \mathbb{N}_0^2 \times \mathbb{N}_0^2$, the $(x, y)$-component $(1_{n,m})_{x,y}$ of $1_{n,m}$ is given by

$$\text{If } n = x \text{ and } m = y, \quad (1_{n,m})_{x,y} = 1; \quad \text{else, } (1_{n,m})_{x,y} = 0.$$

(4.2)

For $\omega \in I^N$ and $k \in \mathbb{N}$ we define the matrix $A_0(\omega, k) \in \mathbb{R}^{N_0 \times N_0}$ given by

$$A_0(\omega, k) := A_0(\omega, 1)A_0(\sigma\omega, 1) \cdots A_0(\sigma^{k-1}\omega, 1) \in \mathbb{R}^{N_0 \times N_0},$$

where the matrix product $A_0(\tau, 1) \cdot A_0(\upsilon, 1) \in \mathbb{R}^{N_0 \times N_0}$ is for $\tau, \upsilon \in I^N$ and $l, m \in N_0^s$ given by

$$\text{if } \tau = \upsilon, \quad (A_0(\tau, 1) \cdot A_0(\upsilon, 1))_{l, m} := \sum_{k \in \mathbb{N}_0} (A_0(\tau, 1))_{l, k} \cdot (A_0(\upsilon, 1))_{k, m}.$$

Moreover, let $p_{\omega_k} := p_{\omega_1}p_{\omega_2} \cdots p_{\omega_k}$ and define

$$A(\omega, k) := (p_{\omega_k})^{-1}A_0(\omega, k) \in \mathbb{R}^{N_0 \times N_0}.$$

Also, for $a, b \in \widehat{\mathbb{C}}$ we define

$$U(a, b) := (u_n(a, b))_{n \in \mathbb{N}_0} \in \mathbb{R}^{N_0^s}, \quad \text{where } u_n(a, b) := C_n(a) - C_n(b).$$

Finally, for $n, m \in \mathbb{N}_0^s$ we write $n \leq m$ if $n_i \leq m_i$ for all $1 \leq i \leq s$.

Remark. Note that (4.3) in Definition 4.2 is well defined, since there exist only finitely many non-zero entries in each row of the matrix $A_0(\tau, 1) \in \mathbb{R}^{N_0 \times N_0}$. In the following we will frequently make use of the product of matrices with an infinite index set, which requires explanation. These matrix products will always be well defined, since either the first factor of the product possesses at most finitely many non-zero entries in each row, or the second factor contains at most finitely many non-zero entries in each column.

To state the next lemma, we introduce the following matrices.

Definition 4.3. For $i \in \{1, \ldots, s\}$ we introduce the $\mathbb{N}_0^s$-matrix $D_i$ given by

$$D_i = \sum_{n \in \mathbb{N}_0} n_i 1_{n, n - e_i}.$$ 

Next lemma shows that the matrix cocycle $A$ is commutative.

Lemma 4.4. Let $k \in \mathbb{N}$ and $i_1, i_2, \ldots, i_k \in \{1, \ldots, s\}$. Put $t_l = \text{card}\{ j \leq k \mid i_j = l\}, \quad l = 1, \ldots, s$ and let $\mathbf{t} = (t_l)_{l \leq s} \in \mathbb{N}_0^s$. Then for every $u, v \in N_0^s$, we have

$$\text{(4.4) } (D_{i_1} \cdots D_{i_k})_{u,v} = \begin{cases} \prod_{l=1}^{s} u_l \cdot (u_l - 1) \cdots (u_l - t_l + 1), & \text{if } v = u - \mathbf{t} \\ 0, & \text{else.} \end{cases}$$

In particular, the matrices $(D_i)_{i=1}^{s}$ commute. Moreover, for all $\omega, \tau \in I^N$ we have

$$A(\omega, 1)A(\tau, 1) = A(\tau, 1)A(\omega, 1) \quad \text{and} \quad A_0(\omega, 1)A_0(\tau, 1) = A_0(\tau, 1)A_0(\omega, 1).$$
Proof. We only consider the case when \( k = 2 \). The general case is left to the reader. Let \( i, j \in \{1, \ldots, s\} \). The following calculation proves (4.4). See (4.2) for the definition of \( \mathbf{1}_{n,m} \). We have

\[
D_i \cdot D_j = \left( \sum_{n \in \mathbb{N}_0} n_j \mathbf{1}_{n,n} - \mathbf{e}_i \right) \left( \sum_{n \in \mathbb{N}_0} n_j \mathbf{1}_{n,n} - \mathbf{e}_j \right)
= \sum_{r \in \mathbb{N}_0} \left( \sum_{n \in \mathbb{N}_0} n_j \mathbf{1}_{n,n} - \mathbf{e}_i \right) \left( \sum_{n \in \mathbb{N}_0} n_j \mathbf{1}_{n,n} - \mathbf{e}_j \right)
= \begin{cases} u_i \cdot (u - e_j), & \text{if } v = u - e_i - e_j \\ 0, & \text{else.} \end{cases}
\]

We see from (4.4) that the matrices \((D_i)_i\) commute. By the definition of \( A_0 \) we have \( A_0(\omega, 1) = p_{\omega 0} \text{id} + D_{\omega 1}, \) if \( \omega_1 \neq s + 1 \), where \( \text{id} = \sum \mathbf{1}_{n,n} \), and \( A_0(\omega, 1) = p_{r + 1} \text{id} - \sum_{r=1}^{s} D_i, \) if \( \omega_1 = s + 1 \). Consequently, the commutativity of \( A_0(\omega, 1) \) and \( A_0(\tau, 1) \) follows. Thus, the commutativity of \( A(\omega, 1) \) and \( A(\tau, 1) \) follows. The proof is complete.

The following lemma is easy to show by using the definition of \( A(\omega, k) \) and induction on \( k \) (see also the argument in the proof of Lemma 4.4).

Lemma 4.5. Let \( \omega \in J_0 \) and \( k \in \mathbb{N} \). Then \( A(\omega, k)_{n,n} = 1 \) for every \( n \in \mathbb{N}_0 \). Also, \( A(\omega, k)_{n,m} = 0 \) unless \( m \leq n \).

The following lemma is easy to see by assumption (2) of our paper.

Lemma 4.6. There exists \( \varepsilon_0 > 0 \) such that if \( z \in f_i^{-1}(J(G)) \) and \( j \neq i \) then \( f_j(B(z, \varepsilon_0)) \) is included in a connected component of \( F(G) \).

In the following, we fix an element \( \varepsilon_0 > 0 \) given in Lemma 4.6.

Lemma 4.7. Let \( \omega \in J_0 \), \( z \in J_0 \) and \( k_0 \in \mathbb{N} \). Let \( a, b \in \mathbb{C} \) and suppose that \( f_{\omega_{i,k}}(a), f_{\omega_{i,k}}(b) \in B(f_{\omega_{i,k}}(z), \varepsilon_0) \) for all \( 0 \leq k \leq k_0 - 1 \), where \( f_{\omega_{i,0}} = \text{id} \). Then

\[
U(a, b) = A_0(\omega, k)U(f_{\omega_{i,k}}(a), f_{\omega_{i,k}}(b)), \quad 1 \leq k \leq k_0.
\]

That is, for each \( n \in \mathbb{N}_0 \) we have

\[
u_n(a, b) = \sum_{m \in \mathbb{N}_0} A_0(\omega, k)_{n,m} u_m(f_{\omega_{i,k}}(a), f_{\omega_{i,k}}(b)) = \sum_{m \in \mathbb{N}_0; m \leq n} A_0(\omega, k)_{n,m} u_m(f_{\omega_{i,k}}(a), f_{\omega_{i,k}}(b)).
\]

Moreover, if \( u_0(a, b) \neq 0 \) then

\[
(u_0(a, b))^{-1} U(a, b) = \left( u_0(f_{\omega_{i,k}}(a), f_{\omega_{i,k}}(b)) \right)^{-1} A(\omega, k)U(f_{\omega_{i,k}}(a), f_{\omega_{i,k}}(b)).
\]

Proof. To prove the first assertion, it suffices to consider \( k = 1 \). Then general case then follows by induction on \( k \). By Lemma 4.1 we have for \( n \in \mathbb{N}_0 \),

\[
u_n(a, b) = C_n(a) - C_n(b) = M(C_n)(a) - M(C_n)(b) + \sum_{i=1}^{s} n_i (C_{n-e_i}(f_i(a)) - C_{n-e_i}(f_i(b))) - \sum_{i=1}^{s} n_i (C_{n-e_i}(f_{s+1}(a)) - C_{n-e_i}(f_{s+1}(b))).
\]
Now first suppose that $\omega_1 \neq s + 1$. Since $C_0$ and hence all its partial derivatives $C \in \mathcal{C}$ are locally constant on $F(G)$ (see [Sum11a, Theorem 3.15 (1)]), by the choice of $\ell_0$, we have

$$u_n(a,b) = p_{\omega_0}(C_n(f_{\omega_0}(a)) - C_n(f_{\omega_0}(b))) + n_{\omega_0}(C_{n-e_{\omega_0}}(f_{\omega_0}(a)) - C_{n-e_{\omega_0}}(f_{\omega_0}(b))) = (A_0(\omega, 1)U(f_{\omega_0}(a), f_{\omega_0}(b)))_n.$$ 

Similarly, if $\omega_1 = s + 1$ then we have

$$u_n(a,b) = p_{\omega_0}(C_n(f_{\omega_0}(a)) - C_n(f_{\omega_0}(b))) - \sum_{i=1}^s m_i(C_{n-e_i}(f_{s+1}(a)) - C_{n-e_i}(f_{s+1}(b))) = (A_0(\omega, 1)U(f_{s+1}(a), f_{s+1}(b)))_n.$$ 

The second assertion follows from the first by using $u_0(a,b) = p_{\omega_0}(f_{\omega_0}(a), f_{\omega_0}(b))$.

We now prove the key lemma in which we estimate the polynomial growth order of the components of $A(\omega, k)$ as $k \to \infty$.

**Lemma 4.8.** Let $\omega \in \ell^N$ and $k \in \mathbb{N}$. Put $m_i := m_i(k) := \text{card}\{1 \leq j \leq k : \omega_j = i\}$ for $1 \leq i \leq s + 1$. Let $m = (m_i)_{i=1}^s \in \mathbb{N}_0^s$. Let $q, r \in \mathbb{N}_0^s$ with $0 \leq r \leq q$. Then we have

$$A(\omega, k)_{q,r} = \sum_{\text{q-r-m} \leq \text{t} \leq \text{q-r}} \left( (-1)^{|t|} p_{s+1}^{-|t|} \left( m_{s+1} \right)_t \prod_{i=1}^s \left( \frac{m_i}{(q_i - r_i - t_i)!} \right) \frac{q_i!}{(m_i - (q_i - r_i - t_i))! (q_i - r_i - t_i)! r_i! p_i^{q_i - r_i - t_i}} \right),$$

where $t = (t_i)_{1 \leq i \leq s}$. In particular, there exists a constant $K \geq 1$ which depends only on $q$ and the probability vector $p$ but not on $k$ such that

$$|A(\omega, k)_{q,r}| \leq K \left( \prod_{i=1}^s m_i^{q_i - r_i} \right) m_{s+1}^{q_{s+1} - r_{s+1}} \text{ and } |A(\omega, k)_{q,r}| \leq Kk^{|q|}.$$ 

If $\omega_j \neq s + 1$ for all $1 \leq j \leq k$ and $m_i > q_i - r_i$ for all $1 \leq i \leq s$, then there exists $K' > 0$ depending only on $q$ such that

$$A(\omega, k)_{q,r} \geq K' \prod_{i=1}^s m_i^{q_i - r_i}.$$ 

**Proof.** By Lemma 4.4 we have

$$(4.5) \hspace{1cm} A(\omega, k) = \prod_{i=1}^s \left( \text{id} + p_i^{-1} D_i \right)^{m_i} \left( \text{id} - p_i^{-1} \sum_{i=1}^s D_i \right)^{m_{s+1}}.$$ 

To expand the right-hand side, we use the multinomial coefficient, which is given by $(\alpha_1, \alpha_2, \ldots, \alpha_n)^{\beta} = \frac{n!}{\prod_{i=1}^n \alpha_i}$ and which satisfies

$$(x_1 + x_2 + \ldots + x_n)^n = \sum_{|\alpha| = n} \frac{n!}{\prod_{i=1}^n \alpha_i} x_1^{\alpha_1} x_2^{\alpha_2} \ldots x_n^{\alpha_n}.$$ 

By (4.5) and Lemma 4.4 we obtain, for each $q, r$ with $0 \leq r \leq q$,

$$(A(\omega, k))_{q,r} = \sum_{0 \leq \text{t} \leq \text{q-r-m}} \sum_{|\alpha| = m_{s+1}} \left( \frac{|\alpha|}{|\alpha'_1|} \right) \prod_{i=1}^s \left( \frac{m_i}{(q_i - r_i - t_i)!} \right) \frac{q_i!}{(m_i - (q_i - r_i - t_i))! (q_i - r_i - t_i)! r_i! p_i^{q_i - r_i - t_i}}.$$ 

Note that, to deduce the above formula, when we expand the term $\left( \text{id} - p_i^{-1} \sum_{i=1}^s D_i \right)^{m_{s+1}}$ on the right hand side of (4.5), for any $t$ with $q - r - m \leq t \leq q - r$, $0 \leq |t| \leq m_{s+1}$, and for any subset $\mathcal{S} \subseteq \{1, \ldots, m_{s+1}\}$ with $|\mathcal{S}| = |t|$, we picked the factor $-p_i^{-1} \sum_{i=1}^s D_i$ for any element $j \in \mathcal{S}$, and we picked the identity
for any element $j \in \{1, \ldots, s\} \setminus \mathcal{J}_{s+1}$. Finally, a simple calculation finishes the proof of the first assertion of the lemma.

For the upper bound of $|A(\omega, k)_{\mathbf{q}, \mathbf{r}}|$ we observe that with some constant $K_0$ which depends on $\mathbf{q}$ and the probability vector $\mathbf{p}$ but not on $k$ we have

\[
p_{s+1}^{-|\mathbf{q}|} \frac{m_{s+1}}{(m_{s+1} - 1)!} \leq K_0_m_{s+1}^{-|\mathbf{q}|} \prod_{i=1}^{s} \frac{m_i^{q_i}!}{(m_i - (q_i - r_i - 1))!} (q_i - r_i - 1)! r_i! p_i^{q_i - r_i - 1} \leq K_0 \left( \prod_{i=1}^{s} m_i^{q_i - r_i} \right) m_s^{q_s - |\mathbf{r}|}.
\]

Since $\sum_{i=1}^{s+1} m_i = k$ we see that $m_{s+1}^{-|\mathbf{q}|} \prod_{i=1}^{s} m_i^{q_i - r_i - 1} \leq k^{\mathbf{q}}$.

Now suppose that $\omega_j \neq s + 1$ for all $1 \leq j \leq k$ and $m_i > q_i - r_i$ for $1 \leq i \leq s$. Then we have

\[
A(\omega, k)_{\mathbf{q}, \mathbf{r}} = \prod_{i=1}^{s} \frac{m_i^{q_i}!}{(m_i - (q_i - r_i))!} (q_i - r_i)! r_i! p_i^{q_i - r_i}.
\]

Clearly, with some constant $K''$ which depends only on $\mathbf{q}$ we have that

\[
\frac{m_i^{q_i}!}{(m_i - (q_i - r_i))!} (q_i - r_i)! r_i! p_i^{q_i - r_i} \geq K'' m_i^{q_i - r_i},
\]

which finishes the proof of the lower bound.

\begin{lemma}
Let $x_0 \in J(G)$ and let $\varepsilon > 0$. Let $n \in \mathbb{N}_0$ and set $n := |\mathbf{n}|$. Then there exists a constant $K > 0$ such that for every $k \in \mathbb{N}$ there exist points $a_k \in B(x_0, \varepsilon) \cap J(G) \setminus \{x_0\}$ and $b_k \in B(x_0, \varepsilon) \setminus \{x_0\}$ with $u_0(a_k, b_k) \neq 0$ such that for $0 \leq q \leq n$,

\[
K^{-1} \sum_{i=1}^{s} q_i (n+1)^{i-1} \leq \frac{u_0(a_k, b_k)}{u_0(a_k, b_k)} \leq Kk \sum_{i=1}^{s} q_i (n+1)^{i-1}.
\]

\end{lemma}

\begin{proof}
By the density of the repelling fixed points in $J(G)$ ([HM96, Theorem 3.1]) there exist $z_0 \in B(x_0, \varepsilon)$ and $g \in G$ such that $g(z_0) = z_0$ and $|g'(z_0)| > 1$. Since $\deg(g) \geq 2$ we have $E(g) \subset P(g) \subset P(G)$, where $E(g) = E(\langle g \rangle)$ denotes the set of exceptional points of $g$. Since $G$ is hyperbolic we have $J(G) \subset \hat{\mathbb{C}} \setminus P(G) \subset \hat{\mathbb{C}} \setminus E(g)$. We may assume that $g(B(z_0, \varepsilon)) \supset B(z_0, \varepsilon)$. Moreover, we have $\bigcup_{n \in \mathbb{N}} g^n(B(z_0, \varepsilon)) = \hat{\mathbb{C}} \setminus E(g)$. Hence, there exists $n \in \mathbb{N}$ such that $J(G) \subset g^n(B(z_0, \varepsilon))$. We may assume that $n = 1$ and $J(G) \subset g(B(x_0, \varepsilon))$.

Since $C_0$ is not locally constant on any neighborhood of any point of $J(G)$ (see [Sum11a, Lemma 3.75]) and since $J(G)$ is an uncountable perfect set (see [HM96, Lemma 3.11]), there exist $a \in J(G) \setminus \{x_0\}$ and $b \in \hat{\mathbb{C}} \setminus \{x_0\}$ close to $a$ such that $C_0(a) \neq C_0(b)$.

For each $k \in \mathbb{N}$ and $1 \leq i \leq s$ we set $m_i(k) := k^{(n+1)^{i-1}}$. Then we define $h_k := f_1^{m_1(k)} \ldots f_s^{m_s(k)}$. Since $G$ is hyperbolic, we have $P(G) \subset F(G)$. For each connected component $U$ of $F(G)$, we take the hyperbolic metric on $U$. For each connected component $U$ of $F(G)$ with $U \cap P(G) \neq \emptyset$, let $B_0(P(G) \cap U, 1)$ be the 1-neighborhood of $P(G) \cap U$ in $U$ with respect to the hyperbolic metric on $U$. Let $V = \cup B_0(P(G) \cap U, 1)$, where the union is taken over all connected components $U$ of $F(G)$ with $U \cap P(G) \neq \emptyset$. Then $G(V) \subset V$, $V \subset F(G)$ and $J(G) \subset \hat{\mathbb{C}} \setminus V$. Since $a \in J(G)$, there exist $\eta > 0$ and a holomorphic inverse branch $\gamma_0 : B(a, \eta) \to \hat{\mathbb{C}}$ such that $h_0 \circ \gamma_0 = \id_{B(a, \eta)}$, for each $k \in \mathbb{N}$. We may assume that $b \in B(a, \eta)$. Set $\tilde{a}_k := \gamma_0(a_k)$.

Since $G(V) \subset V$, we have that $(\gamma_k)_{k \in \mathbb{N}}$ is normal in $B(a, \eta)$. Thus we may assume that

\[
d(\tilde{a}_k, \tilde{b}_k) \leq \delta \quad \text{for all } k \in \mathbb{N}, \quad \text{where } \delta > 0 \text{ is a small number.}
\]

Since $\tilde{a}_k \in J(G)$, there exists $\tilde{a}_k \in J(G) \cap B(x_0, \varepsilon)$ with $g(\tilde{a}_k) = \tilde{a}_k$ for all $k \in \mathbb{N}$. By making $\delta$ sufficiently small, we can find $b_k \in B(x_0, \varepsilon)$ with $g(b_k) = b_k$.

We write $g = f_1 \circ \cdots \circ f_s$ for some $r \in \mathbb{N}$ and $\tau = (\tau_1, \ldots, \tau_r) \in I'$. Put $\bar{\tau} := (\tau_1, \ldots, \tau_r, \tau_1, \ldots, \tau_r, \ldots) \in \bar{I}^\mathbb{N}$.

Since $M(C_0) = C_0$, $C_0$ is locally constant on $F(G)$ ([Sum11a, Theorem 3.15 (1)]) and $C_0(a) = C_0(b) \neq 0$, if
\( \delta \) is small enough, then Lemma 4.6 implies that \( u_0(a_k, b_k) = C_0(a_k) - C_0(b_k) \neq 0 \) and \( u_0(\tilde{a}_k, \tilde{b}_k) = C_0(\tilde{a}_k) - C_0(\tilde{b}_k) \neq 0 \). Since \( g(a_k) = \tilde{a}_k \) and \( g(b_k) = \tilde{b}_k \), Lemma 4.7 and \( J(G) = \bigcup_{\alpha \in \mathcal{P}_d} J_{\alpha} \) (Lemma 3.3) yield
\[
(u_0(a_k, b_k))^{-1} U(a_k, b_k) = (u_0(\tilde{a}_k, \tilde{b}_k))^{-1} A(\tau, r) U(\tilde{a}_k, \tilde{b}_k).
\]
Put \( \xi_k := (1, 2^m, \ldots, s^m) \in \mathcal{I}_{s}^{m} \) where \( u^m := (u, u, \ldots, u) \in I^m \) for \( u \in \{1, \ldots, s+1\} \). Since \( h_k(\tilde{a}_k) = a \) and \( h_k(\tilde{b}_k) = b \), we have by Lemmas 4.7 and 4.4,
\[
(u_0(\tilde{a}_k, \tilde{b}_k))^{-1} U(\tilde{a}_k, \tilde{b}_k) = (u_0(a, b))^{-1} A \left( \xi, \sum_{i=1}^{m} m_i(k) \right) U(a, b).
\]
By combining the previous two equalities (4.6) (4.7) we have
\[
(u_0(a_k, b_k))^{-1} U(a_k, b_k) = (u_0(a, b))^{-1} A(\tau, r) A \left( \xi, \sum_{i=1}^{m} m_i(k) \right) U(a, b).
\]
Since \( h_k \in \{f_1, \ldots, f_s\} \), it follows from Lemma 4.8 that for \( q \leq n \),
\[
\left( A \left( \xi, \sum_{i=1}^{m} m_i(k) \right) U(a, b) \right)_{q} \asymp \prod_{i=1}^{r}(m_i(k))^{d_i} \asymp k^{\sum_{i=1}^{m} q(n-1 di)} \quad \text{as } k \to \infty,
\]
where for any two non-negative functions \( \phi_1(k) \) and \( \phi_2(k) \) of \( k \in \mathbb{N} \), we write \( \phi_1(k) \asymp \phi_2(k) \) as \( k \to \infty \) if there exists a constant \( D > 1 \) such that \( D^{-1} \phi_2(k) \leq \phi_1(k) \leq D\phi_2(k) \) for every \( k \in \mathbb{N} \). Also by Lemma 4.5, we have
\[
\left( A(\tau, r) A \left( \xi, \sum_{i=1}^{m} m_i(k) \right) U(a, b) \right)_{q} = \sum_{r \leq q} A(\tau, r)_{q,r} \left( A \left( \xi, \sum_{i=1}^{m} m_i(k) \right) U(a, b) \right)_{r}
\]
and \( A(\tau, r)_{q,q} = 1 \). The proof is complete. \( \square \)

**Lemma 4.10.** Let \( m \in \mathbb{N} \) and \( 0 \leq w_1 < w_2 < \cdots < w_m \) be natural numbers and let \( K \geq 1 \) be a constant. Then there exist \( 0 \leq d_1 < d_2 < \cdots < d_m \) and \( \ell_0 \in \mathbb{N} \) such that for all \( \ell \geq \ell_0 \) and for all \( B \in \mathbb{R}^{m \times m} \) satisfying
\[
K^{-1} f^{\ell di} \leq B_{ij} \leq K f^{\ell di}, \quad \text{for all } i, j \leq m,
\]
we have
\[
\det(B) \geq 1.
\]

**Proof.** The proof is by induction on \( m \in \mathbb{N} \). Let \( 0 \leq w_1 < w_2 < \cdots < w_m < w_{m+1} \). By induction hypothesis there exist \( 0 \leq d_1 < d_2 < \cdots < d_m \) and \( \ell_0 \) for the sequence \( 0 \leq w_1 < w_2 < \cdots < w_m \). Let \( d_m+1 \in \mathbb{N} \) and let \( B \in \mathbb{R}^{(m+1) \times (m+1)} \) be a matrix satisfying \( K^{-1} f^{\ell di} \leq B_{ij} \leq K f^{\ell di} \), for each \( i, j \leq m+1 \) and for all \( \ell \geq \ell_0 \).

Put \( B' := (B_{ij})_{i,j \leq m} \in \mathbb{R}^{m \times m} \). By the Laplace expansion of \( \det(B) \) along the \( (m+1) \)th column, we see that
\[
\det(B) \geq K^{-1} f^{\ell di} \det(B') + O(f^{\ell di} (f^{\ell di} m)^m) \quad \text{as } \ell \to \infty.
\]
Since
\[
\frac{f^{\ell di} m^m \cdot m^{d_m+1}}{f^{\ell di} m^{d_m+1}} = \frac{f^{\ell di} m^m \cdot m^{d_m+1} + m^{d_m+1}}{f^{\ell di} m^{d_m+1} + m^{d_m+1}} \overset{\ell \to \infty}{\longrightarrow} e^{f^{\ell di} m^{d_m+1}} m^{d_m+1},
\]
we see that, for \( d_m+1 \) sufficiently large, we have \( f^{\ell di} m^m \ | e^{f^{\ell di} m^{d_m+1}} m^{d_m+1} | \overset{l \to \infty}{\longrightarrow} 0 \).

Since our induction hypothesis, we have \( \det(B') \geq 1 \) for \( \ell \geq \ell_0 \), the lemma follows. \( \square \)

**Proposition 4.11.** Let \( x_0 \in \mathcal{J}(G) \) and let \( \varepsilon > 0 \). Let \( n \in \mathbb{N}^+ \). Then there exist families \( (a'_r)_{r \leq n} \) and \( (b'_r)_{r \leq n} \) with \( a'_r \in B(x_0, \varepsilon) \cap \mathcal{J}(G) \) \( \setminus \{x_0\} \), \( b'_r \in B(x_0, \varepsilon) \setminus \{x_0\} \) and \( u_0(a'_r, b'_r) \neq 0 \) for all \( r \leq n \), such that the matrix
\[
(u_0(a'_r, b'_r))_{r \leq n}
\]
is invertible.
Proof. Put \( n := |n| \). Define \( t : \{ q : q \leq n \} \to \mathbb{N} \) given by \( t(q) := \sum_{i=1}^{q} q_i (n+1)^{i-1} \). By Lemma 4.9 there exists a constant \( K > 0 \) such that for every \( k \in \mathbb{N} \) there exist points \( a_k \in B(x_0, \varepsilon) \cap J(G) \setminus \{ x_0 \} \) and \( b_k \in B(x_0, \varepsilon) \setminus \{ x_0 \} \) with \( u_0(a_k, b_k) \neq 0 \) such that for \( 0 \leq q \leq n 
exists \frac{u_q(a_k, b_k)}{u_0(a_k, b_k)} \leq Kn^{t(q)}.

Since \( q_i \leq n \) we have that the numbers \( t(q), q \leq n \), are pairwise distinct. We put the elements \( t(q), q \leq n \) in increasing order and denote them by \( w_1 < w_2 < \cdots < w_m \), where \( m := \text{card} \{ q : q \leq n \} \). Let \( d_1 < \cdots < d_m \in \mathbb{N} \) and \( \ell_0 \in \mathbb{N} \) be the elements given by Lemma 4.10 for the sequence \( w_1 < w_2 < \cdots < w_m \) and the constant \( K \). Put \( e(r) := d_i(r), h(r) := \ell_0(r) \) and define

\[
\alpha_r^{(r)} := h(r).
\]

Hence, by Lemma 4.10 we have that \( \left( \frac{u_q(a_k, b_k)}{u_0(a_k, b_k)} \right)_{q \leq n} \) is invertible. The proof is complete. \( \square \)

5. Proof of Theorem 1.1

In this section, we give the proof of Theorem 1.1.

5.1. Lower bound of the pointwise Hölder exponent.

Lemma 5.1. Let \( C = \sum_n \beta_n C_n \in \mathcal{C} \) be non-trivial. Let \( \omega \in \tilde{J}^i, z \in J_\omega \) and \( n \in \mathbb{N}_0 \). Then

\[
\text{Hölder}(\sum_n \beta_n C_n, z) \geq \liminf_{k \to \infty} \frac{S_k \psi(\omega, z)}{S_k \phi(\omega, z)}.
\]

Proof. Let \( V \) be a neighborhood of \( P(G) \) in \( F(G) \) as in the proof of Lemma 4.9. Then \( V \subset F(G) \) and \( G(V) \subset V \). Let \( R > 0 \) such that \( B(J(G), R) \subset \tilde{C} \setminus \tilde{V} \). Then for each \( k \in \mathbb{N} \), there exists a holomorphic branch \( \phi_k : B(f_{\omega_j}(z), R) \to \tilde{C} \) of \( f_{\omega_k} \) such that \( f_{\omega_j}(\phi_k(y)) = y \) for \( y \in B(f_{\omega_j}(z), R) \) and \( \phi_k(f_{\omega_j}(z)) = z \). Since \( G(V) \subset V \), for every \( \varepsilon > 0 \) there exists \( r_0 \leq R \) such that, for the sets \( B_k, \) which are for \( k \in \mathbb{N} \) given by

\[
B_k := \phi_k(B(f_{\omega_j}(z), r_0)),
\]

we have that \( \text{diam}(f_{\omega_j}(B_k)) \leq \varepsilon \) for all \( 1 \leq j \leq k \). Set \( m_i(k) = \text{card} \{ 1 \leq j \leq k : \omega_j = i \} \) for \( 1 \leq i \leq s \). Let \( \mathbf{n}_{\text{max}} \in \mathbb{N}_0^s \) be an element such that for every \( n \in \mathbb{N}_0^s \) with \( \beta_n \neq 0 \), we have \( n \leq \mathbf{n}_{\text{max}} \). Taking \( \varepsilon > 0 \) such that \( 0 < \varepsilon < \varepsilon_0 \), by Lemma 4.7 and Lemma 4.8 there exists \( K \geq 1 \) such that

\[
\sup_{y \in B_k} |C(y) - C(z)| = \sup_{y \in B_k} \left| \sum_{n \leq \mathbf{n}_{\text{max}}} \beta_n (C_n(y) - C_n(z)) \right| = p_{\omega_k} \left( \sup_{y \in B_k} \left| \sum_{n \leq \mathbf{n}_{\text{max}}} \beta_n \left( \sum_{j \leq n} A(\omega, k)_{n,j} \cdot u(j, f_{\omega_j}(y), f_{\omega_j}(z)) \right) \right| \right) \leq p_{\omega_k} \sum_{n \leq \mathbf{n}_{\text{max}}} \beta_n \left( \text{card} \{ j : j \leq \mathbf{n}_{\text{max}} \} \cdot KK_{\mathbf{n}_{\text{max}}} \cdot \max_{j \leq \mathbf{n}_{\text{max}}} \|C_j\| \right).
\]

We have thus shown that

\[
\log \sup_{y \in B_k} |C(y) - C(z)| \leq S_k \psi(\omega, z) + \log \left( \sum_{n \leq \mathbf{n}_{\text{max}}} \beta_n \left( \text{card} \{ j : j \leq \mathbf{n}_{\text{max}} \} \cdot KK_{\mathbf{n}_{\text{max}}} \cdot \max_{j \leq \mathbf{n}_{\text{max}}} \|C_j\| \right) \right).
\]

By [JS15a, Lemma 5.1] and Koebe’s distortion theorem (see also the proof of [JS15a, Lemma 5.2]) we have

\[
\text{Hölder}(C, z) = \liminf_{k \to \infty} \frac{\log \sup_{y \in B_k} |C(y) - C(z)|}{\log r} = \liminf_{k \to \infty} \frac{\log \sup_{y \in B_k} |C(y) - C(z)|}{\frac{S_k \phi(\omega, z)}{k}}.
\]
Thus, \( \| \| \) we have for all \( a \) all its diagonal elements equal to one (see Lemma 5.3.

Let \( \sum B_\mathbf{n} \in \mathcal{C} \) be a sequence of positive integers such that \( j(k) \to \infty \) as \( k \to \infty \). Then for every \( \epsilon > 0 \) there exist \( a, b \in B(x_0, \epsilon) \setminus \{x_0\} \) with \( a \neq b \) such that

\[
\eta := \limsup_{k \to \infty} \left| \sum_{m \leq n_{\max}, n \leq n_{\max}} \beta_n A(\omega, j(k)) n_m m_m(a, b) \right| \in (0, \infty].
\]

Proof. First recall that the matrix \((A(\omega, k))_n_m n \leq n_{\max}, m \leq n_{\max}\) is invertible, since it is a triangular matrix with all its diagonal elements equal to one (see Lemma 4.5). Since \( \{\beta_n\}_n \neq 0 \) we conclude that, for all \( k \in \mathbb{N} \),

\[
\lambda(k) := (\lambda_m(k))_m \leq n_{\max} := \left( \sum_{n \leq n_{\max}} \beta_n A(\omega, j(k)) n_m \right)_{m \leq n_{\max}} \neq 0.
\]

Let \( \epsilon > 0 \) and now suppose by way of contradiction that \( \eta = 0 \) for all \( a, b \in B(x_0, \epsilon) \setminus \{x_0\} \) with \( a \neq b \). Then we have for all \( a, b \in B(x_0, \epsilon) \setminus \{x_0\} \),

\[
(5.3) \quad \sum_{n \leq n_{\max}} \lambda_m(k) u_m(a, b) = 0.
\]

Since \( \lambda(k) \neq 0 \) we may define \( \lambda_{m,0}(k) := \lambda_m(k)/\| (\lambda_p(k))_{p \leq n_{\max}} \|. \) Here, for every \( \mathbf{y} = (y_p)_{p \leq n_{\max}} \), we set \( \| \mathbf{y} \| = \| (y_p)_{p \leq n_{\max}} \| = \sqrt{\sum_{p \leq n_{\max}} |y_p|^2} \). By passing to a subsequence \((j(k))_{k \in \mathbb{N}}\) of \((j(k))_{k \in \mathbb{N}}\) we may assume that \( \lambda_{m,0}(k) := \lim_{k \to \infty} \lambda_{m,0}(k) \in \mathbb{C} \) exists for each \( m \leq n_{\max} \). Put \( \lambda := (\lambda_m)_{m \leq n_{\max}} \) and observe that \( \| \lambda \| = 1 \). Let \( \mathbf{r} \) be a maximal element in \( \{n : n \leq n_{\max}, \beta_n \neq 0\} \) with respect to \( \leq \). Then by Lemma 4.5,

\[
\sum_{n \leq n_{\max}} \beta_n A(\omega, j(k))_{n, \mathbf{r}} = \beta_\mathbf{r} A(\omega, j(k))_{\mathbf{r}, \mathbf{r}} = \beta_\mathbf{r}, \quad \text{for every } \ell \in \mathbb{N}.
\]

Thus, \( \| (\lambda_p(k))_{p \leq n_{\max}} \| \geq \| \beta_\mathbf{r} \| > 0 \) for every \( \ell \in \mathbb{N} \). Hence, it follows from (5.3) that

\[
\sum_{n \leq n_{\max}} \lambda_n u_n(a, b) = 0, \quad \text{for all } a, b \in B(x_0, \epsilon) \setminus \{x_0\},
\]

which yields \( \lambda = 0 \) by Proposition 4.11. This is the desired contradiction which completes the proof of the lemma.

Lemma 5.3. Let \( \sum_n \beta_n C_n \in \mathcal{C} \) be non-trivial. Let \( \omega \in \mathcal{D}, z \in J_\omega \) and \( \mathbf{n} \in \mathbb{N}_0^\omega \). Then

\[
\text{Höf}(\sum_n \beta_n C_n, z) \leq \liminf_{k \to \infty} \frac{S_k \psi(\omega, z)}{S_k \phi(\omega, z)}.
\]

Proof. We may assume that there exists a sequence \((j(k))_{k \in \mathbb{N}}\) tending to infinity such that

\[
\lim_{k \to \infty} \frac{S_{j(k)} \psi(\omega, z)}{S_{j(k)} \phi(\omega, z)} = \alpha.
\]
Moreover, since $f_{\omega(jk)}(z) \in J_{\sigma_{jk}(a)} \subset J(G)$ and $J(G)$ is compact, we may assume that $x_0 := \lim_k f_{\omega(jk)}(z)$ exists. Let $V, R$ be as in the proof of Lemma 5.1. Then for each $p \in \mathbb{N}$, there exists a holomorphic branch $\phi_p : B(f_{\omega(j)}(z), R) \to \mathbb{C}$ such that $f_{\omega(j)}(\phi_p(y)) = y$ for $y \in B(f_{\omega(j)}(z), R)$ and $\phi_p(f_{\omega(j)}(z)) = z$.

Since $G(V) \subset V$, by taking $R$ so small, we may assume that $f_{\omega(j)}(\phi_p(B(f_{\omega(j)}(z), R))) \subset B(f_{\omega(j)}(z), \epsilon_0)$ for all $p, q \in \mathbb{N} \cup \{0\}$ with $0 \leq q \leq p$, where $\epsilon_0$ is the number given in Lemma 4.6. Let $\epsilon > 0$. By Lemma 5.2 there exist $a, b \in B(x_0, \epsilon) \setminus \{x_0\}$ such that

$$
\eta := \limsup_{k \to \infty} \left| \sum_{m \leq n_{\max}} \sum_{n_{\min} \leq n \leq n_{\max}} \beta_n A(\omega, j(k))_{n,m} u_m(a, b) \right| \in (0, \infty].
$$

After passing to a subsequence of $(j(k))_{k \in \mathbb{N}}$ if necessary, we may assume that

$$
\eta = \lim_{k \to \infty} \left| \sum_{m \leq n_{\max}} \sum_{n_{\min} \leq n \leq n_{\max}} \beta_n A(\omega, j(k))_{n,m} u_m(a, b) \right| \in (0, \infty].
$$

For sufficiently large $k \in \mathbb{N}$ and $\epsilon$ small, we may assume that $a, b \in B(f_{\omega(jk)}(z), R)$. We set $y_k := \phi_{jk}(a)$ and $z_k := \phi_{jk}(b)$. Let $n_{\max} \in \mathbb{N}_{0}$ such that if $n \in \mathbb{N}_{0}, \beta_n \neq 0$ then $n \leq n_{\max}$. By Lemma 4.7 we have

$$
C(y_k) - C(z_k) = \sum_{n \leq n_{\max}} \beta_n (C_n(y_k) - C_n(z_k))
$$

$$
= p_{\omega(jk)} \sum_{n \leq n_{\max}} \beta_n \sum_{m \leq n} A(\omega, j(k))_{n,m} u_m(a, b)
$$

$$
= p_{\omega(jk)} \sum_{m \leq n_{\max}} \left( \sum_{n \leq n_{\max}} \beta_n A(\omega, j(k))_{n,m} \right) u_m(a, b).
$$

Let $\eta_0 \in (0, \eta)$. Since $S_{j(k)}(\tilde{\varphi}) < 0$ for all large $k$ (see the proof of Lemma 5.1), it follows that

$$
\liminf_{k \to \infty} \frac{\log \left| C(y_k) - C(z_k) \right|}{S_{j(k)}(\tilde{\varphi}(\omega, z))} \leq \liminf_{k \to \infty} \frac{S_{j(k)}(\tilde{\varphi}(\omega, z) + \log \eta_0)}{S_{j(k)}(\tilde{\varphi}(\omega, z))} = \alpha.
$$

By Koebe’s distortion theorem we have

$$
\liminf_{k \to \infty} \frac{\log \left| C(y_k) - C(z_k) \right|}{\log \left| d(y_k, z_k) \right|} \leq \alpha.
$$

Finally, we show that Höl(C, z) \leq \beta. To prove this, we show that Höl(C, z) \leq \beta for every $\beta > \alpha$. Suppose by way of contradiction that Höl(C, z) > $\beta$. By the triangle inequality we have

$$
|C(y_k) - C(z_k)| \geq \left| |C(y_k) - C(z_k)| - |C(z_k) - C(z)| \right|.
$$

By Koebe’s distortion theorem we have that $d(y_k, z_k) \sim d(y_k, z_k) \sim d(z_k, z)$ as $k$ tends to infinity. Consequently, by combining with (5.5), we see that there exists a constant $K > 1$ such that

$$
\frac{|C(y_k) - C(z)|}{d(y_k, z_k)^\beta} \geq K^{-1} \frac{|C(y_k) - C(z_k)|}{d(y_k, z_k)^\beta} - K \frac{|C(z_k) - C(z)|}{d(z_k, z)^\beta}.
$$

Our assumption Höl(C, z) > $\beta$ implies that

$$
\lim_{k \to \infty} \frac{|C(z_k) - C(z)|}{d(z_k, z)^\beta} = 0 \quad \text{and} \quad \lim_{k \to \infty} \frac{|C(y_k) - C(z_k)|}{d(y_k, z_k)^\beta} = 0.
$$

Moreover, by (5.4) and our assumption that $\beta > \alpha$ we have $\limsup_k |C(y_k) - C(z_k)|/d(y_k, z_k)^\beta = \infty$. Now (5.6) gives the desired contradiction and finishes the proof of the lemma.

We conclude that Theorem 1.1 follows from combining Lemmas 5.1 and 5.3.
6. Proofs of Theorems 1.2 and 1.3

In this section, we give the proofs of Theorems 1.2 and 1.3. The proof of Theorem 1.2 will follow from the detailed version Theorem 6.1 stated below. For $C \in \mathcal{C}$ and $z \in \hat{C}$ we define the quantities

$$Q_*(C, z) := \liminf_{r \to 0} \frac{\log Q(C, z, r)}{\log r}, \quad Q^*(C, z) := \limsup_{r \to 0} \frac{\log Q(C, z, r)}{\log r} \quad \text{and} \quad Q(C, z) := \lim_{r \to 0} \frac{\log Q(C, z, r)}{\log r},$$

where $Q(C, z, r)$ is for $r > 0$ given by

$$Q(C, z, r) := \sup_{y \in B(z, r)} |C(y) - C(z)|.$$

Moreover, we define for each $\alpha \in \mathbb{R}$ the corresponding level sets

$$R_*(C, \alpha) := \left\{ y \in \hat{C} : Q_*(C, y) = \alpha \right\}, \quad R^*(C, \alpha) := \left\{ y \in \hat{C} : Q^*(C, y) = \alpha \right\}$$

and

$$R(C, \alpha) := \left\{ y \in \hat{C} : Q(C, y) = \alpha \right\}.$$

Also, we define the dynamically defined level sets $\mathcal{F}(\alpha)$, which are for $\alpha \in \mathbb{R}$ given by

$$\mathcal{F}(\alpha) := \pi \left( \hat{\mathcal{F}}(\alpha) \right), \quad \hat{\mathcal{F}}(\alpha) := \left\{ (\omega, x) \in J^1(\hat{f}) : \lim_{n \to \infty} \frac{S_n \psi(\omega, x)}{S_n} = \alpha \right\}.$$ 

Moreover, for $\alpha \in \mathbb{R}$ we set

$$\hat{\mathcal{F}}'(\alpha) := \pi \left( \hat{\mathcal{F}}'(\alpha) \right), \quad \hat{\mathcal{F}}'(\alpha) := \left\{ (\omega, x) \in J^1(\hat{f}) : \lim_{n \to \infty} \frac{S_n \psi(\omega, x)}{S_n} = \alpha \right\}.$$

The free energy function is defined by the unique function $t : \mathbb{R} \to \mathbb{R}$ such that $\mathcal{P}(\beta \hat{\psi} + t(\beta) \hat{f}, \hat{f}) = 0$ for each $\beta \in \mathbb{R}$, where $\mathcal{P}(\cdot, \hat{f})$ denotes the topological pressure with respect to the dynamical system $(J(\hat{f}), \hat{f})$ (cf. [Wal82]). The number $t(0)$ is also referred to as the critical exponent $\delta$ of the rational semigroup $G = \langle f_1, \ldots, f_{r+1} \rangle$ (see [Sum05]). Note that under assumptions (1)(2) of our paper, we have

$$\delta = \dim_H(J(G))$$

([Sum98, Sum05]). The convex conjugate of $t$ ([Roc70, Section 12]) is given by

$$t^* : \mathbb{R} \to \mathbb{R} \cup \{\infty\}, \quad t^*(c) := \sup_{\beta \in \mathbb{R}} \{\beta c - t(\beta)\}, \quad c \in \mathbb{R}.$$ 

We now present the theorem.

**Theorem 6.1.** Every non-trivial $C \in \mathcal{C}$ satisfies all of the following.

1. We have $\alpha_+ = \sup \left\{ \alpha \in \mathbb{R} : R(C, \alpha) \neq \varnothing \right\}$ and $\alpha_- = \inf \left\{ \alpha \in \mathbb{R} : R(C, \alpha) \neq \varnothing \right\}$. Moreover, $R$ can be replaced by $R_*$ or $R^*$. Moreover, we have $\alpha_- = \inf \{ \alpha \in \mathbb{R} : \mathcal{F}(\alpha) \neq \varnothing \}$ and $\alpha_+ = \sup \{ \alpha \in \mathbb{R} : \mathcal{F}(\alpha) \neq \varnothing \}$.
2. Let $\alpha_0 := -t'(0)$. If $\alpha_- < \alpha_+$ then for each $\alpha \in (\alpha_- , \alpha_+)$, we have $\mathcal{F}(\alpha) \subset \mathcal{F}'(\alpha) = H(C, \alpha)$ and

$$\dim_H(\mathcal{F}(\alpha)) = \dim_H(\mathcal{F}'(\alpha)) = \dim_H(R_*(C, \alpha)) = \dim_H(R^*(C, \alpha)) = \dim_H(R(C, \alpha)) = \dim_H(H(C, \alpha)) = -t^*(-\alpha) > 0.$$

Moreover, $v(\alpha) := -t^*(-\alpha)$ is a real analytic strictly concave positive function on $(\alpha_- , \alpha_+)$ with maximum value $\dim_H(J(G)) = \delta = -t^*(-\alpha_0) > 0$. Also, $v'' < 0$ on $(\alpha_- , \alpha_+)$.
3. (a) We have $\alpha_- = \alpha_+$ if and only if there exist an automorphism $\varphi \in \text{Aut}(\hat{C})$ and $a_1, \ldots, a_{r+1} \in \mathbb{C}$ such that

$$\varphi \circ f_i \circ \varphi^{-1}(z) = a_i z^{\deg(f_i)} \quad \text{and} \quad \log \deg(f_i) = -\left(\gamma/\delta\right) \log p_i,$$

where $\gamma$ denotes the unique number such that $\mathcal{P}(\gamma \hat{\psi}, \hat{f}) = 0$. 

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(b) If $\alpha_- = \alpha_+$ then we have
\[ \mathcal{F}(\alpha_0) = R^* (C, \alpha_0) = R (C, \alpha_0) = H (C, \alpha_0) = J (G), \]
and for all $\alpha \in \mathbb{R}$ with $\alpha \neq \alpha_0$ we have
\[ \mathcal{F}(\alpha) = R^* (C, \alpha) = R (C, \alpha) = H (C, \alpha) = H (C, \alpha) = \varnothing. \]

Proof. The assertions follow by combining Theorem 1.1 with [JS15a, Theorem 5.3], which completes the proof of the theorem. \qed

We now give the proof of Theorem 1.3.

Proof. By [Sum98] and [Sum05, Remark 5], assumption (1) of this paper is equivalent to the property that the associated skew product map $\tilde{f}$ is expanding in the sense of [Sum05] and [JS15a]. By [Sum05] or [JS15a] again, we have that $(J(\tilde{f}), \tilde{f})$ is a topological transitive expanding dynamical system with compact state space. Thus, there exists a surjective Hölder continuous morphism from an irreducible Markov shift over a finite alphabet. The Markov shift $(\Sigma_A, \sigma)$ is given by the shift space
\[ \Sigma_A := \left\{ \omega = (\omega_i)_{i \in \mathbb{N}} \in V^\mathbb{N} \mid A(\omega_i, \omega_{i+1}) = 1 \text{ for all } i \in \mathbb{N} \right\}, \]
and the left shift $\sigma : \Sigma_A \to \Sigma_A$, where $V$ is a finite alphabet set and $A \in \{0, 1\}^V \times V$ is an irreducible incidence matrix. We endow $\Sigma_A$ with the metric
\[ d_\Sigma (\omega, \tau) := 2^{-\sup \{n \geq 0 \mid \omega_n = \tau_n, \ldots, \omega_{n+1} = \tau_{n+1} \}}. \]
It is known (see e.g. [JS15a]) that there exists a surjective Hölder continuous map $\pi : \Sigma_A \to J(\tilde{f})$ such that $\tilde{f} \circ \pi = \pi \circ \sigma$. We define the potentials $\psi : \Sigma_A \to \mathbb{R}$, $\varphi : \Sigma_A \to \mathbb{R}$ given by
\[ \psi := \psi \circ \pi, \quad \varphi := \varphi \circ \pi. \]
Note that $\psi$ and $\varphi$ are Hölder continuous. For a function $g : \Sigma_A \to \mathbb{R}$ we write $S_n g := \sum_{j=0}^{n-1} g \circ \sigma^j$. If $g : \Sigma_A \to \mathbb{R}$ is Hölder continuous, then there exists a constant $K_g \geq 1$ such that, for every $k \in \mathbb{N}$, $\omega_1 \ldots \omega_k u \in \Sigma_A$ and $\omega_1 \ldots \omega_k v \in \Sigma_A$,
\[ |S_k g(\omega_1 \ldots \omega_k u) - S_k g(\omega_1 \ldots \omega_k v)| \leq K_g. \]
As in the proof of Lemma 5.1, there exist $m \in \mathbb{N}$ and $\theta < 0$ such that $S_m \varphi \leq \theta < 0$. Since $A$ is irreducible, there exists $l_0 \in \mathbb{N}$ such that for each $k \in \mathbb{N}$ and $\omega \in \Sigma_A^m$ there exists $m \leq \ell \leq l_0$ and $\tau \in \Sigma_A^{\ell}$ such that $\omega \tau := \omega \tau \tau \tau \cdots \in \Sigma_A$. Here, $\Sigma_A^n := \{ \omega = (\omega_i)_{i=1}^n \in V^n : A(\omega_i, \omega_{i+1}) = 1, i = 1, \ldots, n-1 \}$.

By the definition of $\alpha_-$ and $\alpha_+$ and Theorem 1.1 we have
\[ \frac{\sum_{j=0}^{n-1} \psi \circ \tilde{f}^j (x)}{\sum_{j=0}^{n-1} \varphi \circ \tilde{f}^j (x)} = \lim_{n \to \infty} \frac{S_n \psi(\omega)}{S_n \varphi(\omega)} = \lim_{n \to \infty} \frac{\sum_{j=0}^{n-1} \psi \circ \tilde{f}^j (\pi^j(\omega))}{\sum_{j=0}^{n-1} \varphi \circ \tilde{f}^j (\pi^j(\omega))} \in [\alpha_-, \alpha_+]. \]
For each $x \in J(\tilde{f})$ and $k \in \mathbb{N}$ there exists $\omega \in \Sigma_A$ such that $\pi(\omega) = x$. Let $m \leq \ell \leq l_0$ and $\tau \in \Sigma^{\ell}$ such that $(\omega_1 \ldots \omega_\ell \tau) \in \Sigma_A$. Using the bounded distortion property of $\psi$ and $\varphi$ and (6.1) we obtain
\[ \frac{\sum_{j=0}^{n-1} \psi \circ \tilde{f}^j (x)}{\sum_{j=0}^{n-1} \varphi \circ \tilde{f}^j (x)} \geq \frac{S_{km} \psi(\omega)}{S_{km} \varphi(\omega)} \geq \frac{-S_{km} \psi(\omega_1 \ldots \omega_{km} \tau) - K_\psi}{-S_{km} \varphi(\omega_1 \ldots \omega_{km} \tau) + K_\varphi} \geq \frac{S_{km} \psi(\omega_1 \ldots \omega_{km} \tau) - K_\psi - l_0 \max |\psi|}{S_{km} \varphi(\omega_1 \ldots \omega_{km} \tau) + K_\varphi} \geq \frac{S_{km} \psi(\omega_1 \ldots \omega_{km} \tau) \delta(k)}{S_{km} \varphi(\omega_1 \ldots \omega_{km} \tau) \delta(k)} \delta(k) \geq \alpha \cdot \delta(k), \]
where we have set
\[ \delta(k) := \left(1 - \frac{K_\psi + l_0 \max |\psi|}{k \min |S_m \psi|}\right) / \left(1 + \frac{K_\psi}{k \min |S_m \varphi|}\right). \]
Note that $\delta(k) = 1 + O(k^{-1})$ as $k \to \infty$. Let $C \in \mathcal{A}$ be non-trivial and let $z \in J(G)$ with $z = \pi(x)$ for some $x \in J(f)$. We use the notations of the proof of Lemma 5.1. By (5.1) in the proof of Lemma 5.1 there exists $p \in \mathbb{N}$ and $K_1$ (depending only on $C$) such that, for all $k \in \mathbb{N}$,

$$\sup_{y \in B_{km}} |C(y) - C(z)| \leq K_1(km)^p \varepsilon_{\text{sm}}^p(z) = K_1(km)^p \left(e^{\varepsilon_{\text{sm}}(z)}\right)^{\frac{\varepsilon_{\text{sm}}(z)}{2\varepsilon_{\text{sm}}(z)}}.$$  

For $k \in \mathbb{N}$ we have $r_k := e^{\varepsilon_{\text{sm}}(z) \frac{\varepsilon_{\text{sm}}(z)}{2\varepsilon_{\text{sm}}(z)}} < 1$. Consequently, we have

$$\sup_{y \in B_{km}} |C(y) - C(z)| \leq K_1(km)^p r_k^{-\delta(k)}.$$  

Since $\delta(k) = 1 + O(k^{-1})$, as $k \to \infty$, we have

$$r_k^{\delta(k)} = r_k^{1+O(k^{-1})} = r_k \varepsilon^{-O(k^{-1})}, \quad \text{as} \ k \to \infty. $$

Since $\log(r_k)/k = S_{km}/k$ is a bounded sequence, we conclude that there exists a constant $K_2 \geq 1$ such that $r_k^{-\delta(k)} < K_2 r_k$. Thus, since $\alpha_- > 0$, for every $\varepsilon > 0$ we have

$$\sup_{y \in B_{km}} |C(y) - C(z)| \leq K_1(K_2)^{-\alpha_-} (km)^p K_2^{\alpha_-} r_k^{-\alpha_-} r_k^{-\frac{1}{1-\varepsilon}}.$$  

Also, $k^p r_k^{1-\varepsilon} \to 0$ as $k \to \infty$. Combining the above with the Koebe distortion theorem, we obtain that $C$ is $\alpha_- \cdot (1-\varepsilon)$-Hölder continuous. Finally, if $C = C_0$ then the previous estimates hold with $p = 0$ (and hence $\varepsilon = 0$), which implies that $C_0$ is $\alpha_-$-Hölder continuous on $\hat{C}$. The proof of Theorem 1.3 is complete. \hfill \Box

7. PROOF OF THEOREM 1.4

In this section, we give the proof of Theorem 1.4.

Proof. Suppose that $\alpha_- \geq 1$. Then by Theorem 1.2 (1) we have that $C_0$ is a Lipschitz function on $\hat{C}$. Let $K$ be a minimal set of $G$ with $K \neq \emptyset$. By conjugating $G$ by a Möbius transformation, we may assume that $J(G)$ is a subset of $\hat{C}$. Let $ABCD$ be a rectangle such that $AB$ is included in a connected component $U_L$ of $F(G)$ with $U_L \cap L \neq \emptyset$, and $CD$ is included in a connected component $U_K$ of $F(G)$ with $U_K \cap K \neq \emptyset$. Since the 2-dimensional Lebesgue measure of $J(G)$ is zero (actually $\text{dim}_H(J(G)) < 2$), Fubini’s theorem implies that there exists a segment $S$ in $ABCD$ which joins $AB$ and $CD$ such that the 1-dimensional Lebesgue measure of $S \cap J(G)$ is zero. Let us consider $E = C_0|S$. Identify $S$ with $[a, b]$ such that $a \in AB \subset U_L$ and $b \in CD \subset U_K$. Note that by the definition of $C_0$ we have that $E(a) = 1$ and $E(b) = 0$. Since $E$ is Lipschitz, it is almost everywhere differentiable on $S$ with respect to the 1-dimensional Lebesgue measure on $S$ and we have $E(x) = \int_a^x E'(t) \, dt$. But $E$ is locally constant on $S \cap F(G)$, and since the 1-dimensional Lebesgue measure of $S \cap J(G)$ is zero, we have $E'(x) = 0$ almost everywhere on $S$, which implies that $E$ is constant on $S$. This is the desired contradiction which completes the proof of the result $\alpha_- < 1$.

We now let $\alpha \in (\alpha_-, 1)$. Then Theorems 1.1 and 6.1 imply that there exists a Borel subset $A_0$ of $J(G)$ with $\text{dim}_H(A_0) > 0$ such that for every $x \in A_0$ and for every non-trivial $C \in \mathcal{A}$, we have $\text{Hö}l(C,x) = \alpha$. Let $A = \bigcup_{x \in G^{-1}(A_0)}$. Then $\overline{A} = J(G)$ ([HM96, Lemma 3.2]) and $A$ has the desired property. \hfill \Box

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