

A characterization of Thurston’s Master Teapot

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Abstract. We prove an explicit characterization of the points in Thurston’s Master Teapot, which can be implemented algorithmically to test whether a point in $\mathbb{C} \times \mathbb{R}$ belongs to the complement of the Master Teapot. As an application, we show that the intersection of the Master Teapot with the unit cylinder is not symmetrical under reflection through the plane that is the product of the imaginary axis of \mathbb{C} and \mathbb{R} .

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1. Introduction

The *growth rate* of a continuous dynamical system $f : X \rightarrow X$, where X is a compact topological space, is the exponential of the topological entropy of f , $e^{h_{\text{top}}(f)}$. When such a dynamical system admits a Markov partition—as is the case for continuous, multimodal, postcritically finite, self-maps of intervals, or pseudo-Anosov surface diffeomorphisms—a consequence of the Perron–Frobenius theorem is that the growth rate must be a *weak Perron number*, that is, a real, positive algebraic integer that is not less than the absolute value of any of its Galois conjugates. In [Thu14], Thurston proved that every weak Perron number arises as the growth rate of some continuous, multimodal, postcritically finite, self-maps of intervals. (The analogous question for pseudo-Anosov surface diffeomorphisms remains open.) By considering the set of all interval maps of any modality and any postcritical orbit portrait, Thurston stabilized the question; the question of characterizing the set of growth rates of all postcritically finite interval maps of any fixed modality $d \geq 2$ is more subtle, and remains open. This work investigates growth rates of the family of all continuous, unimodal, critically periodic interval self-maps, which we denote \mathcal{F}_2^{cp} .

Since the growth rates of maps in \mathcal{F}_2^{cp} are known to satisfy a condition involving their Galois conjugates (namely, they are weak Perron numbers), it is natural to consider, for any $f \in \mathcal{F}_2^{cp}$, the set $\{z \in \mathbb{C} : z \text{ is a Galois conjugate of the growth rate, } e^{h_{\text{top}}(f)}, \text{ of } f\}$. Another, related reason to consider the set of Galois conjugates of $e^{h_{\text{top}}(f)}$ is that the Galois conjugates can be used to construct a ‘lift’ of this real, one-dimensional dynamical system defined by f to a dynamical system defined on $\mathbb{C}^s \times \mathbb{R}^d$, where r is the number of real Galois conjugates of $e^{h_{\text{top}}(f)}$ and s is the number of non-real complex-conjugate pairs of Galois conjugates (see, e.g., Theorem 2.1 of [Thu14]). The *Master Teapot* for the family \mathcal{F}_2^{cp} is the set

$$\Upsilon_2^{cp} := \overline{\{(z, \lambda) \in \mathbb{C} \times \mathbb{R} \mid \lambda = e^{h_{\text{top}}(f)} \text{ for some } f \in \mathcal{F}_2^{cp}, z \text{ is a Galois conjugate of } \lambda\}}.$$

Thurston coined the term ‘Master Teapot’ because plots of finite approximations of this set resemble a teapot, with a roughly cylindrical body over the unit circle, a ‘spout’ consisting of points of the form $\{\lambda, \lambda\}$, and a ‘handle’ protruding from the body opposite the spout. (See Figure 1.) Clearly, the geometry and topology of this set encode information about which growth rates are realized by maps in the family \mathcal{F}_2^{cp} . While the geometry of the Master Teapot retains information about which growth rate λ corresponds to which Galois conjugate z , it is also interesting to consider the subset of \mathbb{C} formed by plotting all the Galois conjugates (including the growth rate λ) of all maps in \mathcal{F}_2^{cp} in the same copy of \mathbb{C} , and taking the closure. The *Thurston set* is the set

$$\Omega_2^{cp} := \overline{\{z \in \mathbb{C} \mid z \text{ is a Galois conjugate of } e^{h_{\text{top}}(f)} \text{ for some } f \in \mathcal{F}_2^{cp}\}}.$$

Equivalently, the Thurston set is the projection of the Master Teapot to the complex plane.

The Master Teapot and Thurston set have rich and mysterious geometrical and topological structures that have been investigated in several recent works, including [BDLW19, CKW17, Tho17, Thu14, Tio15, Tio18]. Describing the ‘shape’ of the Master Teapot Υ_2^{cp} or the Thurston set Ω_2^{cp} is a step toward refining Thurston’s result by characterizing which weak Perron numbers arise as the growth rates of which PCF interval maps. In particular, the ability to prove that a specific point z is *not* in the Master Teapot—which the algorithms we present in §8 accomplish—provides a necessary condition for a growth rate to be realized by a map in \mathcal{F}_2^{cp} .

In [BDLW19], the authors prove that the Master Teapot Υ_2^{cp} is connected and contains the unit cylinder $S^1 \times [1, 2]$. Furthermore, the intersection of the *height- λ slice of the Master Teapot*,

$$\Xi_\lambda := \{z \in \mathbb{C} : (z, \lambda) \in \Upsilon_2^{cp}\}$$

with the closed unit disk $\overline{\mathbb{D}}$ grows monotonically with λ [BDLW19]. Consequently, the part of the top level slice of the Master Teapot that is inside the unit cylinder, $\Xi_2 \cap \overline{\mathbb{D}}$, coincides with $\Omega_2^{cp} \cap \overline{\mathbb{D}}$, the part of the Thurston set inside the unit disk.

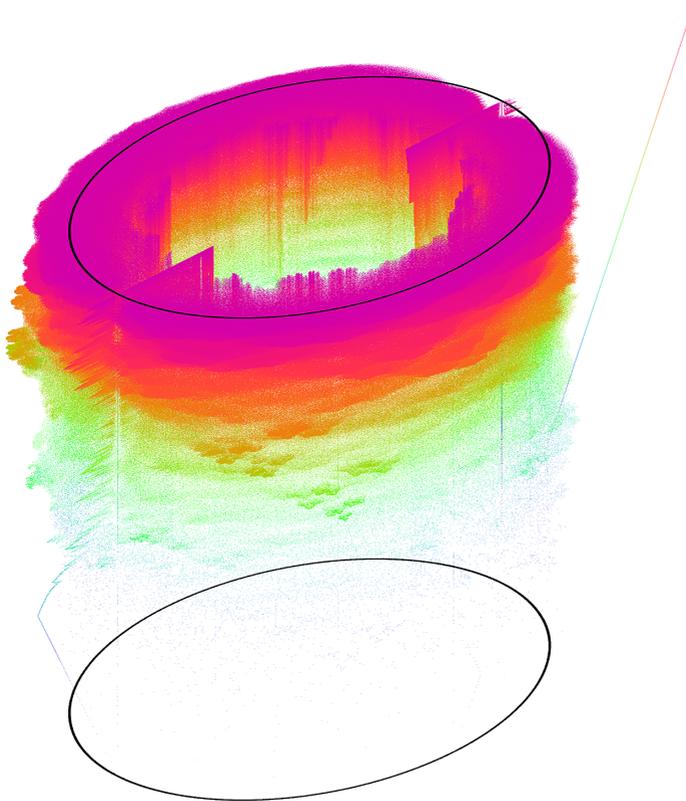


FIGURE 1. A plot of a finite approximation of Υ_2^{cp} , showing all points coming from maps in \mathcal{F}^{cp} whose critical orbits have periods at most 23. The two black circles are $S^1 \times \{1\}$ and $S^1 \times \{2\}$, where S^1 is the unit circle. The color gradients show the height of the plotted points. This figure is from [BDLW19].

The growth rates of PCF self-maps of real intervals may be seen as a specific case of *core entropy* for PCF complex polynomials. Indeed, the filled Julia set of a PCF complex polynomial contains a forward invariant, finite topological tree, called the Hubbard tree, that contains the critical points of the polynomial; the core entropy of such a polynomial is the topological entropy of the restriction of the dynamics to the Hubbard tree. For a polynomial with real coefficients, the Hubbard tree is a real interval, and so the restriction of the map to the Hubbard tree is a PCF multimodal self-map of an interval. Although we confine our investigation here to self-maps of real polynomials, similar questions could be explored in the complex setting. The interested reader may read more about core entropy for complex polynomials in [GT21, Tio16].

Another motivation for investigating PCF multimodal self-maps of real intervals is that these maps may also be seen as one-dimensional analogs of pseudo-Anosov surface diffeomorphisms. A *uniform expander* is a continuous, piecewise affine-linear (with finitely many pieces) self-map of an interval such that the derivative on each piece is $\pm\lambda$ for some expansion factor $\lambda > 1$. Classical results in entropy theory imply that the growth rate of a uniform expander with expansion factor λ is λ . Milnor and Thurston proved that every

continuous, self-map of an interval with finitely many critical points and positive topological entropy is semi-conjugate to a uniform expander with the same topological entropy [MT88]. Both PCF uniform expanders and pseudo-Anosov surface diffeomorphisms are uniformly expanding maps except at finitely many points, admit Markov partitions, and their expansion factors (called the dilatation of a pseudo-Anosov surface diffeomorphism) coincide with their growth rates. Constructions of pseudo-Anosov surface diffeomorphisms from uniform expanders are explored in [BRW16, Far21]. Characterizing the set of dilatations realized by pseudo-Anosov surface diffeomorphisms remains an open question.

The Master Teapot and Thurston set are also closely related to the theory of β - and generalized β -expansions (cf. [DMP11, G07, IS09, LSS16, Ste13]), roots of Littlewood, Newman, and Borwein polynomials (cf. [BEL08, HM14, Kon99, Muk10, OP93, SS06]), and dynamics of iterated function systems (cf. [Ban02, BH85, Sol04, SX03]).

1.1. *Overview of main results.* The main contribution of this paper is an explicit characterization of the Master Teapot Υ_2^{cp} —necessary and sufficient conditions for a point to be in Υ_2^{cp} . (The part of the Master Teapot inside the unit cylinder $\mathbb{D} \times [1, 2]$ is described by Theorem 1.7 and the part outside the unit cylinder by Theorem 1.8.) Theorem 1.7 establishes a new connection between horizontal slices of the Master Teapot and iterated function systems. Specifically, the part in \mathbb{D} of each horizontal slice of the Teapot can be viewed as an analog of the Mandelbrot set for a family of ‘restricted iterated function systems’ (cf. Remark 1.15). From this characterization, we prove an algorithm (§8) for showing that certain weak Perron numbers cannot be the exponent of the topological entropy of a critically periodic unimodal interval map. As an application of this algorithm, we prove that the part of the Master Teapot inside the unit cylinder is not symmetrical with respect to reflection across the imaginary axis (Theorem 1.14). Conjecture 1.16 proposes that an analogy of the Mandelbrot–Julia set correspondence holds for horizontal slices and limit sets of restricted iterated function systems.

1.2. *Precise statement of results and commentary.* To state the results precisely, we introduce some terminology and notation.

First, we define words and sequences in the alphabet $\{0, 1\}$.

Definition 1.1

- (1) A sequence $w = w_1w_2 \dots$ is an element in $\{0, 1\}^{\mathbb{N}}$. The shift map $\sigma : \{0, 1\}^{\mathbb{N}} \rightarrow \{0, 1\}^{\mathbb{N}}$ is defined by removing the first element of a sequence, that is, $\sigma(w_1w_2w_3 \dots) := w_2w_3 \dots$.
- (2) A word $w = w_1w_2 \dots w_n$ is an element in $\{0, 1\}^n$ for some positive integer n . The number n is called the length of the word w and is denoted by $|w|$.
- (3) For $n \in \mathbb{N}$, the reverse function $\text{Rev} : \{0, 1\}^n \rightarrow \{0, 1\}^n$ is defined as

$$\text{Rev}(w_1w_2 \dots w_n) := w_nw_{n-1} \dots w_1.$$

- (4) For $k \in \mathbb{N}$, the k -prefix of a sequence $w = w_1w_2 \dots$ is the word

$$\text{Pre}_k(w) := w_1 \dots w_k.$$

- (5) For a word $w = w_1 \dots w_n$ of length n and a natural number $k \leq n$, the k -prefix and k -suffix of w are the words

$$\begin{aligned} \text{Pre}_k(w) &:= w_1 \dots w_k, \\ \text{Suf}_k(w) &:= w_{n-k+1} w_{n-k+2} \dots w_n. \end{aligned}$$

Next, we relate words and sequences with dynamics on \mathbb{C} via the following definitions.

Definition 1.2

- (1) For any $z \in \mathbb{C}$, define maps $f_{0,z}, f_{1,z} : \mathbb{C} \rightarrow \mathbb{C}$ by

$$f_{0,z}(x) := zx, \quad f_{1,z}(x) := 2 - zx.$$

- (2) For any $w = w_1 \dots w_n$ and $z \in \mathbb{C}$, set

$$F(w, z) := f_{w_n,z} \circ \dots \circ f_{w_1,z}(1).$$

- (3) For any sequence $w = w_1 w_2 \dots$ and any $z \in \mathbb{C}$ with $|z| > 1$, set

$$\begin{aligned} H(w, z) &:= \lim_{n \rightarrow \infty} (-1)^{(\sum_{i=1}^n w_i)} z^{-n} F(\text{Pre}_n(w), z) \\ &= \lim_{n \rightarrow \infty} (-1)^{(\sum_{i=1}^n w_i)} z^{-n} f_{w_n,z} \circ \dots \circ f_{w_1,z}(1). \end{aligned}$$

- (4) For any sequence $w = w_1 w_2 \dots$ and $z \in \mathbb{C}$ with $|z| < 1$, set

$$\begin{aligned} G(w, z) &:= \lim_{n \rightarrow \infty} F(\text{Rev}(\text{Pre}_n(w)), z) \\ &= \lim_{n \rightarrow \infty} f_{w_1,z} \circ \dots \circ f_{w_n,z}(1). \end{aligned}$$

The following definition is partly from [MT88].

Definition 1.3

- (1) The *cumulative sign* of a word $w = w_1 w_2 \dots w_n$ is defined as $s(w) := (-1)^{\sum_i w_i}$.
- (2) The *twisted lexicographic order* \leq_E is a total ordering on the set of sequences, defined as follows: $w <_E w'$ if and only if there is some $k \in \mathbb{N}$ such that $\text{Pre}_{k-1}(w) = \text{Pre}_{k-1}(w')$, and $s(\text{Pre}_{k-1}(w))(w'_k - w_k) > 0$. In other words, $w <_E w'$ if and only if, denoting by k the index of the first letter where w and w' differ, either $w'_k > w_k$ and the common $(k - 1)$ -prefix has positive cumulative sign, or $w'_k < w_k$ and the common $(k - 1)$ -prefix has negative cumulative sign.
- (3) We define the total order \leq_E on the set of words of length n exactly the same way as above.

Definition 1.4

- (1) Let $\lambda \in (1, 2]$. We call the map $f_\lambda : [0, 1] \rightarrow [0, 1]$ given by

$$f_\lambda(x) = \begin{cases} \lambda x, & x \leq 1/\lambda, \\ 2 - \lambda x, & x > 1/\lambda, \end{cases}$$

the λ -tent map. Let $I_{0,\lambda} = [0, 1/\lambda], I_{1,\lambda} = [1/\lambda, 1]$.

- (2) The λ -itinerary, denoted as It_λ , is the minimum (with respect to \leq_E) sequence w such that for any $k \geq 0$, $f_\lambda^k(1) \in I_{w_{k+1}, \lambda}$.

One can easily check that It_λ is the itinerary of 1 under f_λ in the convention of the Milnor–Thurston kneading theory.

Now we introduce a combinatorial condition on sequences.

Definition 1.5. For $\lambda \in (1, 2]$, a sequence w is called λ -suitable if for every $\lambda' \in (\lambda, 2]$, the following conditions hold:

- (1) $\text{Rev}(\text{Pre}_n(w)) \leq_E \text{Pre}_n(\text{It}_{\lambda'})$ for all $n \in \mathbb{N}$;
- (2) if $\text{Rev}(\text{Pre}_n(w)) = \text{Pre}_n(\text{It}_{\lambda'})$, then the cumulative sign $s(\text{Pre}_n(w)) = -1$;
- (3) if $\text{It}_{\lambda'} = 1 \cdot 0^k \cdot 1 \dots$, $k \in \mathbb{N}$, then w does not contain $k + 1$ consecutive 0s (that is, if $\text{It}_{\lambda'}$ starts with 1 followed by k 0s and then 1, writing w as $w = w_1 w_2 \dots$, there does not exist $n \in \mathbb{N}$ such that $w_i = 0$ for all $n \leq i \leq n + k$);
- (4) if $k \in \mathbb{N}$ satisfies $\sqrt{2} \leq \lambda^{2^k} < 2$, then $w = \mathfrak{D}'^k(w')$ for some sequence w' , where \mathfrak{D}' is the map that replaces 0 with 11 and 1 with 01, such that for every $\lambda' > \lambda^{2^k}$, if $\text{It}_{\lambda'} = 1 \cdot 0^k \cdot 1 \dots$, then w' does not contain $k + 1$ consecutive 0s.

Remark 1.6. Every sequence is (vacuously) 2-suitable.

For $\lambda \in (1, 2)$, let Ξ_λ be a height- λ slice of the Master Teapot Υ_2 :

$$\Xi_\lambda := \{z : (z, \lambda) \in \Upsilon_2\}.$$

We will use the following notation:

- $\mathbb{D} := \{z \in \mathbb{C} : |z| < 1\}$ the open unit disk,
- $\overline{\mathbb{D}} := \{z \in \mathbb{C} : |z| \leq 1\}$ the closed unit disk,
- $S^1 := \{z \in \mathbb{C} : |z| = 1\}$ the unit circle,
- $\mathcal{C} := \overline{\mathbb{D}} \times [1, 2]$ the closed ‘unit cylinder’.

Our main theorem is the following.

THEOREM 1.7. *For any $\lambda \in (1, 2]$, the part of the slice Ξ_λ inside the closed unit disk can be characterized as*

$$\Xi_\lambda \cap \overline{\mathbb{D}} = S^1 \cup \{z \in \mathbb{D} : G(w, z) = 1 \text{ for some } \lambda\text{-suitable sequence } w\}.$$

There is a similar characterization for outside the unit disc, which follows directly from results in [Tio18].

THEOREM 1.8. *For any $\lambda \in (1, 2)$, the part of the slice Ξ_λ outside the unit disk can be characterized as follows.*

- If the λ -tent map is not critically periodic, then

$$\Xi_\lambda \setminus \overline{\mathbb{D}} = \{z \in \mathbb{C} \setminus \overline{\mathbb{D}} : H(\text{It}_\lambda, z) = 0\}.$$

- If the λ -tent map is critically periodic with period p , then

$$\Xi_\lambda \setminus \overline{\mathbb{D}} = \{z \in \mathbb{C} \setminus \overline{\mathbb{D}} : H(\text{It}_\lambda, z) = 0 \text{ or } z^p = 2\}.$$

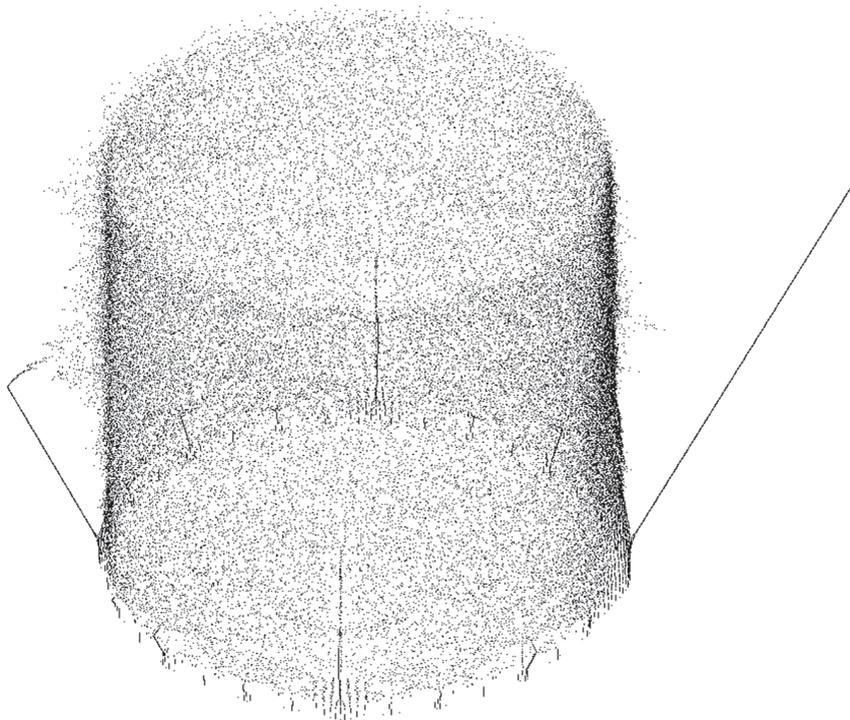


FIGURE 2. A constructive approximation of the part of Υ_2^{cp} outside the unit cylinder. This plot shows the 56 737 points outside the cylinder $S^1 \times [1, 2]$ that are roots of the degree 100 partial sums of the kneading power series for 1000 different growth rates λ in $[1, 2]$. The ‘spout’ on the right side of the image consists of points of the form (λ, λ) .

Remark 1.9. Theorems 1.7 and 1.8 both provide algorithms to certify that a point is in the complement of Ξ_λ . This is useful since the definition of Υ_2^{cp} is not constructive, as it involves taking a closure. Section 8 describes these algorithms. Figure 4 is a finite approximation of $\Xi_{1.8} \cap \overline{\mathbb{D}}$ using Theorem 1.7, and Figure 2 is a finite approximation of $\Upsilon_2^{cp} \setminus (\overline{\mathbb{D}} \times [1, 2])$ using Theorem 1.8.

Remark 1.10. Since the set of λ -suitable sequences is semicontinuous with λ (Lemma 5.5), Theorem 1.7 implies that if $1 < \lambda < \lambda' \leq 2$, then

$$\Xi_\lambda \cap \overline{\mathbb{D}} \subseteq \Xi_{\lambda'} \cap \overline{\mathbb{D}},$$

which is the ‘persistence theorem’ proved in [BDLW19]. However, our proof of Theorem 1.7 depends on the persistence theorem in [BDLW19].

Remark 1.11. Tiozzo showed in [Tio18] that

$$\Omega_2^{cp} \cap \overline{\mathbb{D}} = S^1 \cup \{z \in \mathbb{D} : G(w, z) = 1 \text{ for some sequence } w\},$$

and the persistence theorem [BDLW19] shows that $\Omega_2 \cap \overline{\mathbb{D}} = \Xi_2 \cap \overline{\mathbb{D}}$. It is also known that the unit cylinder is in the teapot, that is, $S^1 \times [1, 2] \subset \Upsilon_2^{cp}$ [BDLW19]. Since every

sequence is 2-suitable, this proves the conclusion of Theorem 1.7 for the top level of the teapot, the case $\lambda = 2$.

Remark 1.12. Our first step towards proving Theorem 1.7 is proving Theorem 4.5, an alternative characterization of slices $\Xi_\lambda \cap \overline{\mathbb{D}}$. A corollary of Theorem 4.5 is that all roots in $\overline{\mathbb{D}}$ of all Parry polynomials coming from admissible words—even reducible Parry polynomials—are in the Thurston set Ω_2^{cp} .

COROLLARY 1.13. $\Omega_2^{cp} \cap \overline{\mathbb{D}}$ is the closure of the set of all roots in $\overline{\mathbb{D}}$ of all Parry polynomials associated to admissible words.

In particular, when using Parry polynomials to plot approximations of Ω_2^{cp} , it is not necessary to check whether the Parry polynomials are irreducible.

As an application of Theorem 1.7, we will show the following.

THEOREM 1.14. The part of the Master Teapot inside the unit cylinder is not symmetrical with respect to reflection across the imaginary axis, that is, $\Upsilon_2^{cp} \cap \mathcal{C}$ is not invariant under the map $(z, \lambda) \mapsto (-z, \lambda)$.

Since Galois conjugates occur in complex conjugate pairs, it is immediate that $(x + iy, \lambda) \in \Upsilon_2^{cp}$ if and only if $(x - iy, \lambda) \in \Upsilon_2^{cp}$.

Theorem 1.14 is surprising because the Thurston set, Ω_2^{cp} , which is the projection to \mathbb{C} of Υ_2^{cp} , is symmetrical under the map $z \mapsto -z$ (Proposition 9.1). However, this asymmetry in the Master Teapot is confined to the slices of heights $\geq \sqrt{2}$; one can prove, via the renormalization procedure described in §2.3, that the unit cylinder part of slices of height $< \sqrt{2}$ is symmetrical under reflection across the imaginary axis.

Remark 1.15. Theorem 1.7 allow us to interpret each slice $\Xi_\lambda \cap \mathbb{D}$ as an analogy of the Mandelbrot set. The conclusion of Theorem 1.7 for the top slice (cf. Remark 1.11) allows one to characterize Ξ_2 as the union of S_1 and the set of all parameters $z \in \mathbb{D}$ such that the point 1 is an element of the limit set Λ_z associated to the iterated function system generated by $f_{0,z}$ and $f_{1,z}$. Theorem 1.7 suggests viewing $\Xi_\lambda \cap \mathbb{D}$ as the set of parameters z for which the point 1 is an element of the ‘limit set’ associated to the ‘restricted iterated function system’ generated by $f_{0,z}$ and $f_{1,z}$ in which only the compositions represented by λ -suitable sequences are allowed.

Based on numerical experiments, we propose the following conjectured analogy of the Julia–Mandelbrot correspondence [DH85, Lei90].

Conjecture 1.16. For any complex number $|z| < 1$, any $\lambda \in (1, 2]$, the set $\{z' - z : z' \in \Xi_\lambda\}$ is asymptotically similar to the set

$$J_z = \{G(w, z) - 1 : w \text{ is } \lambda\text{-suitable}\}.$$

By these two sets being asymptotically similar, we mean there exists a real number $r > 0$ and sequences $(t_n), (t'_n) \in \mathbb{C}$ with $t_n, t'_n \rightarrow \infty$ such that, denoting Hausdorff

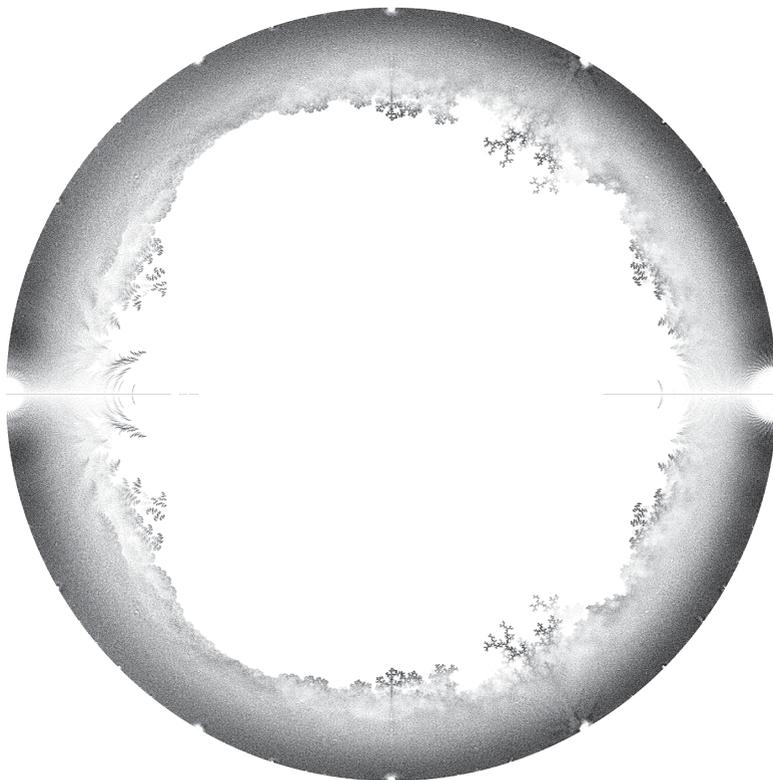


FIGURE 3. A constructive plot of an approximation of the slice $\Xi_{1.8} \cap \mathbb{D}$. The plotted black points are all the roots of modulus ≤ 1 of all Parry polynomials for superattracting tent maps with growth rate < 1.8 and critical length at most 29.

distance by d_{Haus} ,

$$\lim_{n \rightarrow \infty} d_{\text{Haus}}(\overline{B_r(0)} \cap (t_n(\Xi_\lambda - z)), \overline{B_r(0)} \cap (t'_n J_z)) = 0.$$

If Conjecture 1.16 is true, or at least true for ‘enough’ points z , we would also be able to show the following.

Conjecture 1.17. There exists $\lambda \in (1, 2)$ such that $\Xi_\lambda \cap \overline{\mathbb{D}}$ has infinitely many connected components.

Figure 3 shows a constructive plot (in black) of the slice $\Xi_{1.8} \cap \overline{\mathbb{D}}$, while Figure 4 shows (in white) points of $\overline{\mathbb{D}} \setminus \Xi_{1.8}$. Comparison of these images suggests the existence of multiple small connected components in the region $\text{Re}(z) < 0$ near the inner boundary of the ‘ring.’

The Thurston set Ω_2^{cp} is known to be path-connected and locally connected [Tio18, Theorem 1.3]. It follows from Theorem 1.8 that for many heights $\lambda \in (1, 2]$, the part of the slice of height λ that is outside the unit cylinder consists of more than one connected component.



FIGURE 4. The upper half of the slice $\Upsilon_2^{cp} \cap (\mathbb{D} \times \{1.8\})$ plotted using Theorem 1.7. Specifically, the plotted white points are shown to be in the complement of Υ_2^{cp} (by checking the condition of Theorem 1.7 for all $m \leq 18$).

Conjecture 1.17 could be potentially proven by computation via an effective version of Theorem 1.7 similar to Proposition 8.4. However, a tighter bound than that obtained in Proposition 8.4 would probably be needed for the computation to be feasible.

The structure of the paper is as follows.

Section 2 provides definitions and notation for Parry polynomials, admissible and dominant words and sequences, growth rates, and the renormalization/doubling operators.

Section 3 proves some elementary results about the doubling map which we will need in later sections to extend results about the top part of the teapot to the part with height $< \sqrt{2}$.

Section 4 proves Theorem 4.5, which implies that all roots in the unit disk of all Parry polynomials associated to admissible words are in the teapot.

Section 5 discusses λ -suitability and proves Lemma 5.7, which is the key combinatorial result we need to prove Theorem 1.7.

Section 6 uses Theorem 4.5 and Lemma 5.7 to prove Theorem 1.7.

Section 7 proves Theorem 1.8.

Section 8 presents algorithms, derived from Theorems 1.7 and 1.8, which will detect if a point $(z, \lambda) \in \mathbb{C} \times \mathbb{R}$ belongs to the complement of the height- λ slice Ξ_λ , and proves lemmas that justify the algorithms.

Section 9 proves Theorem 1.14 by exhibiting a point (z, λ) that is in the teapot and using the algorithm from §8 to prove that $(-\bar{z}, \lambda)$ is in the complement of the slice Ξ_λ .

2. Preliminaries

2.1. *Concatenation.* We use \cdot or just adjacency to denote concatenations, that is, for any word $w = w_1 \dots w_n$ and any word or sequence $v = v_1 v_2 \dots$,

$$w \cdot v = wv = w_1 \dots w_n v_1 v_2 \dots$$

We denote the concatenation of n copies of a word w by w^n for $n \in \mathbb{N} \cup \{\infty\}$.

2.2. *Parry polynomials.* Let w be a word with positive cumulative sign. The *Parry polynomial* of w , $P_w : \mathbb{C} \rightarrow \mathbb{C}$, is defined as

$$P_w(z) := F(w, z) - 1$$

(cf. [BDLW19, Definition 2.7]). It is evident that if $\text{It}_\lambda = w^\infty$, then λ is a root of P_w , and hence all Galois conjugates of λ must be roots of P_w .

One can check by simple bookkeeping that for any word w of positive cumulative sign, $P_w(z)$, $G(\text{Rev}(w)^\infty, z)$ and $H(w^\infty, z)$ satisfy the following relationship.

LEMMA 2.1. *If w is of length n and has positive cumulative sign, then*

$$P_w(z) = (1 - z^n)G(\text{Rev}(w)^\infty, z) = z^n(1 - z^{-n})H(w^\infty, z).$$

2.3. *Admissibility, itineraries, and dominance.* The *shift map* σ is defined on sequences by

$$\sigma(w_1w_2w_3 \dots) = (w_2w_3 \dots).$$

A sequence $w = w_1w_2 \dots$ is a generalized symbolic coding of f_λ for some $\lambda \in (1, 2]$ if and only if

$$f_\lambda^k(1) \in I_{w_{k+1}, \lambda}$$

for every integer $k \geq 0$. Because the point $1/\lambda$ belongs to both intervals $I_{0, \lambda}$ and $I_{1, \lambda}$, there may exist more than one generalized symbolic coding for the itinerary of the point 1 under f_λ . The λ -itinerary It_λ is the least (with respect to \leq_E) such generalized symbolic coding.

A sequence w starting with 10 is called *admissible* if

$$\sigma^k(w) \leq_E w$$

for all $k \in \mathbb{N}$. A word w is called *admissible* if w has positive cumulative sign and w^∞ is admissible.

We will use the following immediate consequence of Theorem 12.1 of [MT88].

THEOREM 2.2. *For every $\lambda \in (1, 2]$, It_λ is admissible.*

PROPOSITION 2.3. [BDLW19] *Let w be a word with positive cumulative sign. If w is admissible and the associated Parry polynomial, $P_w(z)$, can be written as the product of $(z - 1)$ and another irreducible factor, then $w^\infty = \text{It}_\lambda$ for some $\lambda \in (1, 2]$.*

The following is a straightforward corollary [MT88, Theorem 13.1].

COROLLARY 2.4. *If $1 < \lambda < \lambda' \leq 2$, then $\text{It}_\lambda <_E \text{It}_{\lambda'}$.*

A word w is called *dominant* (cf. [BDLW19, Definition 4.1, Lemma 4.2]) if it has positive cumulative sign, and for any $1 \leq k \leq |w| - 1$,

$$\text{Suf}_k(w) \cdot 1 <_E \text{Pre}_{k+1}(w).$$

Every dominant word is admissible, but admissible words may not be dominant. A key property of the dominant words is the following, which is proved in [Tio15] and reviewed in [BDLW19, Proposition 4.4].

PROPOSITION 2.5. *If $\lambda \in (\sqrt{2}, 2)$ and $It_\lambda = w^\infty$, then for any $n > 0$, there exists a word w' such that $w^n w'$ is dominant.*

2.4. *Growth rates and critically periodic tent maps.* When a continuous self-map f of an interval is postcritically finite, the exponential of its topological entropy, $e^{h_{\text{top}}(f)}$, also called its *growth rate*, is a *weak Perron number*—a real positive algebraic integer whose modulus is greater than or equal to that of all of its Galois conjugates. This is because cutting the interval at the critical and postcritical sets yields a Markov partition; each of the resulting subintervals is mapped to a finite union of subintervals. The leading eigenvalue of the associated incidence matrix is $e^{h_{\text{top}}(f)}$, which the Perron–Frobenius theorem implies is a weak Perron number.

In the present work, we consider growth rates of critically periodic unimodal interval self-maps. A unimodal map f is said to be *critically periodic* if, denoting the critical point of f by c , there exists $n \in \mathbb{N}$ such that $f^n(c) = c$. A theorem of Milnor and Thurston [MT88, Theorem 7.4] tells us that, from the point of view of entropy, instead of considering all critically periodic unimodal maps, we only need to consider critically periodic tent maps. For tent maps, it is easy to see that the growth rate is just the slope λ .

2.5. *Renormalization and doubling.* As shown in [BDLW19, §3], for any $1 < \lambda < \sqrt{2}$, the tent map f_λ is critically periodic if and only if the tent map f_{λ^2} is critically periodic. (This phenomenon is related to renormalization of the Mandelbrot set.) Furthermore, whenever $1 < \lambda < \sqrt{2}$, It_λ can be obtained from It_{λ^2} by replacing each 1 in It_λ with 10 and each 0 in It_λ with 11. That is, the *doubling map* $\mathfrak{D} : \{0, 1\}^n \rightarrow \{0, 1\}^{2n}$, $n \in \mathbb{N} \cup \{\infty\}$, defined by

$$\mathfrak{D}(w_1 w_2 \dots) = 1 \cdot (1 - w_1) \cdot 1 \cdot (1 - w_2) \cdot \dots,$$

satisfies $\mathfrak{D}(It_{\lambda^2}) = It_\lambda$ whenever f_λ with $1 < \lambda < 2$ is critically periodic. We say that a sequence w is *renormalizable* if there exists a sequence w' such that $w = \mathfrak{D}(w')$; in this case, we say that w is the *doubling* of w' and call w' the *renormalization* of w . We define renormalizable, doubling, and renormalization for words analogously.

Remark 2.6. The ‘renormalization’ we are considering here is only the period-2 renormalization, that is, the inverse of tuning by the basilica. The reason is that higher order renormalization would create roots in the P_w that are Galois conjugate of the leading root.

3. Properties of the doubling map

The goal of this section is to prove some elementary properties of renormalizable words and sequences that we will use in later sections to extend the results about the part of the teapot above height $\sqrt{2}$ to the lower part.

LEMMA 3.1. *The doubling map \mathfrak{D} preserves the twisted lexicographic ordering \leq_E , cumulative signs, and hence also admissibility.*

Proof. If the number of 1s in a word w equals n , then for any letter a , the number of 1s in $\text{Pre}_{2|w|+1}(\mathfrak{D}(w \cdot a))$ equals $2|w| + 1 - n$. It follows that if n is odd, $w \cdot 1 <_E w \cdot 0$ and $\mathfrak{D}(w \cdot 1) <_E \mathfrak{D}(w \cdot 0)$; if n is even, $w \cdot 0 <_E w \cdot 1$ and $\mathfrak{D}(w \cdot 0) <_E \mathfrak{D}(w \cdot 1)$. Thus, \mathfrak{D} preserves \leq_E . Furthermore, if a word w has positive cumulative sign, then the number, n , of 1s in w is even, implying that $\mathfrak{D}(w)$, which contains $2w - n$ 1s, also has positive cumulative sign. □

LEMMA 3.2. *The doubling map \mathfrak{D} takes itineraries to itineraries. That is, if $\lambda^{2^k} = \lambda'$, then $\mathfrak{D}^k(\text{It}_{\lambda'}) = \text{It}_{\lambda}$.*

Proof. By induction, it is easy to see that we only need to prove it for $k = 1$, that is, $\mathfrak{D}(\text{It}_{\lambda^2}) = \text{It}_{\lambda}$. For any $\lambda \leq \sqrt{2}$, the tent map f_{λ} sends the interval $[2/(\lambda + 1), 1]$ to $[2 - \lambda, 2/(\lambda + 1)]$ and *vice versa*. Hence, f_{λ}^2 is a tent map from $[2/(\lambda + 1), 1]$ of slope λ^2 , and any $x = f_{\lambda}^{2k}(1)$ lies on the left-hand side of the critical point of f_{λ}^2 if and only if x and $f_{\lambda}(x)$ are both to the right of $1/\lambda$, while $f_{\lambda}^{2k}(1)$ lies on the right-hand side of the critical point of f_{λ}^2 if and only if x is to the right of $1/\lambda$ and $f_{\lambda}(x)$ is to the left of $1/\lambda$, and this finishes the proof for the case when It_{λ^2} is not periodic. The case when It_{λ^2} is periodic follows from this argument together with Lemma 3.1. □

PROPOSITION 3.3. *If w is a word with positive cumulative sign and w' is the renormalization of w , then*

$$P_w(z) = \frac{z - 1}{z + 1} P_{w'}(z^2).$$

Proof. Suppose w and w' are words satisfying $\mathfrak{D}(w') = w$. It is easy to see that if $w = w_1 w_2 \dots w_{2n}$ has a positive cumulative sign, then $w' = w'_1 w'_2 \dots w'_n$ also has a positive cumulative sign. So, the proposition follows from the following more general statement: if w' is any word, w is the doubling of w' , then

$$F(w, z) - 1 = \frac{z - 1}{z + 1} (F(w', z^2) - 1). \tag{3.1}$$

We will prove (3.1) using induction on $|w'|$. In the base case, $|w'| = 1$, $w' = 1$, or $w' = 0$, and the statement is true by calculation. Now assume the statement is true for all words w' such that $|w'| \leq n - 1$. Let w' and w be words with $|w'| = n$ and $\mathfrak{D}(w') = w$. Let w'_0 be w' with the last letter removed, and let w_0 be w with the last two letters removed. Then, by the inductive hypothesis,

$$F(w_0, z) - 1 = \frac{z - 1}{z + 1} (F(w'_0, z^2) - 1).$$

We divide the inductive step into two cases.

Case 1: $w'_n = 0$. This implies $w = w_0 \cdot 11$, so

$$\begin{aligned} F(w, z) - 1 &= 2 - z(2 - z(F(w_0, z))) - 1 \\ &= 2 - z\left(2 - z\left(\frac{z-1}{z+1}(F(w'_0, z^2) - 1) + 1\right)\right) - 1 \\ &= \frac{z-1}{z+1}(z^2 F(w'_0, z^2) - 1) \\ &= \frac{z-1}{z+1}(F(w', z^2) - 1). \end{aligned}$$

Case 2: $w'_n = 1$. This implies $w = w_0 \cdot 10$, so

$$\begin{aligned} F(w, z) - 1 &= z(2 - z(F(w_0, z))) - 1 \\ &= z\left(2 - z\left(\frac{z-1}{z+1}(F(w'_0, z^2) - 1) + 1\right)\right) - 1 \\ &= \frac{z-1}{z+1}(2 - z^2 F(w'_0, z^2) - 1) \\ &= \frac{z-1}{z+1}(F(w', z^2) - 1). \end{aligned} \quad \square$$

PROPOSITION 3.4. *Let w be an admissible word. Then w^∞ renormalizable if only if*

$$w^\infty <_E \text{It}_{\sqrt{2}} \quad (= 10 \cdot 1^\infty).$$

Proof. First, it is easy to see that a sequence is renormalizable if and only if all its odd index letters are 1, and a word is renormalizable if and only if it has even length and all its odd indexed letters are 1. Because any admissible word starts with 10, an admissible word w is renormalizable if and only if w^∞ is admissible and renormalizable.

Now suppose w^∞ is admissible and renormalizable. Suppose the second 0 in w^∞ is at the k th location. It suffices to show that $\text{Pre}_{k-1}(w^\infty)$ has positive cumulative sign, which is equivalent to showing that k is even, because the $(k - 1)$ -prefix of w^∞ and $10 \cdot 1^\infty$ are the same. This is an immediate consequence of the admissibility of w^∞ .

Now we prove the other direction. The sequence w^∞ being admissible implies that the first 0 in w^∞ is at the second location. If we can further prove that the distance between any two consecutive 0s is even, then all 0s are at even locations, and hence w^∞ is admissible. Denote by i_k the location of the k th 0. Let k_m be the smallest number such that $i_{k_m} - i_{k_m-1}$ is odd. Then by definition of $<_E$,

$$\sigma^{i_{k_m-1}-1}(w^\infty) >_E 10 \cdot 1^\infty. \quad \square$$

Remark 3.5. By k th renormalization or k th doubling, we mean carrying out the renormalization or doubling on a word or sequence k times. Proposition 3.3 above implies that if w' is the k th renormalization of w , then the roots of P_w not on the unit circle are the (2^k) th roots of the roots of $P_{w'}$ that are not on the unit circle.

Furthermore, because renormalization of sequences preserves $<_E$ (Lemma 3.1), we can apply Proposition 3.4 above repeatedly to show that if the w_k is the k th doubling of $10 \cdot 1^\infty$, w is admissible, and $w^\infty <_E w_k$, then w has a k th renormalization.

4. Roots in \mathbb{D} of reducible Parry polynomials

The purpose of this section is to prove Theorem 4.5, an alternative characterization of sets $\mathbb{E}_\lambda \cap \overline{\mathbb{D}}$, for $\lambda \in (1, 2]$, using the results in [BDLW19]. An upshot of Theorem 4.5 is that we do not need to worry about extraneous roots in \mathbb{D} from reducible Parry polynomials.

We will use the following four results from [BDLW19].

THEOREM 4.1. [BDLW19, Theorem 1 (‘persistence theorem’), Theorem 2] *If $(z, \lambda) \in \Upsilon_2^{cp}$, $|z| \leq 1$, then so is (z, y) for any $y \in [\lambda, 2]$.*

PROPOSITION 4.2. [BDLW19, Lemma 5.3] *Let w_1 be dominant, $w_1 >_E 10 \cdot 1^{|w_1|-2}$, w_2 be admissible, $w_1^\infty >_E w_2^\infty$, and assume that there is some m such that*

$$2m|w_2| > |w_1| > m|w_2|.$$

Then there is some w' , some integer $m' \geq m$, such that $(w_1 w' w_2^{m'})^\infty$ is admissible,

$$|w_1| + |w'| \geq m'|w_2|,$$

and the Parry polynomial $P_{w_1 w' w_2^{m'}}(z)$ can be written as the product of $(z - 1)$ and another polynomial $Q(z)$ such that $Q(z^{2^k})$ is irreducible for all integers $k \geq 0$.

PROPOSITION 4.3. [BDLW19, Lemma 5.5] *If w_2 is an admissible word and $z \in \mathbb{D}$ is a root of P_{w_2} , then for any $\epsilon > 0$, there exists $N \in \mathbb{N}$ such that for any word w_1 and any integer $n \geq N$, $P_{w_1 w_2^n}$ has a root within distance ϵ of z .*

PROPOSITION 4.4. [BDLW19, Lemma 5.7, Remark 5.8] *If $y \in [\sqrt{2}, 2]$, for any $\epsilon > 0$, there exists a dominant word w_1 such that for any word w_2 , the leading root of $P_{w_1 w_2}$ is within distance ϵ of y , and $w_1 >_E 10 \cdot 1^{|w_1|-2}$.*

We now use the above results to establish the following characterization of the sets $\mathbb{E}_\lambda \cap \overline{\mathbb{D}}$, which will be the starting point of our proof of Theorem 1.7.

THEOREM 4.5. *Fix $1 < \lambda < 2$. For each $\lambda' > \lambda$, define $Y_{\lambda'}$ to be the closure of the set of roots in $\overline{\mathbb{D}}$ of all Parry polynomials P_w such that w is admissible and $w^\infty \leq_E \text{It}_{\lambda'}$, union with S^1 , that is,*

$$Y_{\lambda'} := S^1 \cup \overline{\{z \in \overline{\mathbb{D}} : P_w(z) = 0 \text{ for some admissible word } w \text{ such that } w^\infty \leq_E \text{It}_{\lambda'}\}}.$$

Then,

$$\mathbb{E}_\lambda \cap \overline{\mathbb{D}} = \bigcap_{\lambda' > \lambda} Y_{\lambda'}.$$

Remark 4.6. The condition ‘ $w^\infty <_E \text{It}_{\lambda'}$ for every $\lambda' > \lambda$ ’ is different from ‘ $w^\infty \leq \text{It}_\lambda$ ’ because there could exist a symbolic coding for the itinerary of 1 under the tent map f_λ that is $>_E \text{It}_\lambda$.

Proof. For any $1 < \lambda < 2$, let

$$\Xi'_\lambda = \bigcap_{\lambda' > \lambda} Y_{\lambda'}.$$

We will first prove $\Xi_\lambda \subseteq \Xi'_\lambda$. For any λ' , define the set $Z_{\lambda'}$ to be the closure of the set of Galois conjugates of critically periodic growth rates that are at most λ' , union with S^1 . By the persistence theorem, $\lambda_1 < \lambda_2$ implies $Z_{\lambda_1} \subseteq Z_{\lambda_2}$. So if any point $x \in \bigcap_{\lambda' > \lambda} Z_{\lambda'}$, then $x \in \Xi_\lambda$ since Υ_2^{cp} is closed; similarly, if $x \notin \bigcap_{\lambda' > \lambda} Z_{\lambda'}$, then $x \notin \Xi_\lambda$. Hence,

$$\Xi_\lambda \cap \bar{\mathbb{D}} = \bigcap_{\lambda' > \lambda} Z_{\lambda'}.$$

The conclusion will now follow from the statement that $Z_{\lambda'} \subseteq Y_{\lambda'}$ for all λ' . If z is a Galois conjugate of a critically periodic growth rate λ'' that is at most λ' , then z is a root of the Parry polynomial P_w such that $w^\infty = \text{It}_{\lambda''}$, and $\text{It}_{\lambda''} \leq_E \text{It}_{\lambda'}$ by Corollary 2.4. Thus, $Z_{\lambda'} \subseteq Y_{\lambda'}$ for all λ' .

We will now prove $\Xi'_\lambda \subseteq \Xi_\lambda$. To do this, it suffices to show

$$Y_{\lambda'} \subseteq \bigcap_{\lambda'' > \lambda'} Z_{\lambda''}.$$

We first consider the case $\lambda' \geq \sqrt{2}$. Suppose z is the root of some P_w , where w is admissible and the leading root of P_w is no larger than λ' . ($Y_{\lambda'}$ is the closure of all such z terms.) For any $\epsilon > 0$, Proposition 4.4 guarantees the existence of a dominant word w_1 such that for any w_2 , the leading root of $P_{w_1 w_2}$ is in $[\lambda', \lambda' + \epsilon)$ and $w_1 >_E 10 \cdot 1^{|w_1| - 2}$. By monotonicity (Corollary 2.4), $w_1^\infty >_E w^\infty$. Without loss of generality, we may choose w_1 so that its length, $|w_1|$, is arbitrarily big (this is because as we let $\epsilon \rightarrow 0$, we get arbitrarily many such dominant strings, and there are finitely many strings of at most any given length). Thus we may assume that w_1 and w satisfy the assumptions of Proposition 4.2 with the m of Proposition 4.2 being arbitrarily large, and in particular, m is \geq the N of Proposition 4.3 using w for w_2 . Let w_3 be the word constructed by Proposition 4.2. Because w_3 is admissible, has positive cumulative sign, and $P_{w_3}(z)/(z - 1)$ is irreducible, $w_3^\infty = \text{It}_{\lambda_3}$ for some λ_3 by Proposition 2.3. We know $\lambda_3 \in [\lambda', \lambda' + \epsilon)$ because w_3 has the prefix w_1 . Also, any root of P_{w_3} in \mathbb{D} will be a Galois conjugate of λ_3 , and by construction, P_{w_3} has a root close to z . The containment now follows from letting $\epsilon \rightarrow 0$.

Now we deal with the case $1 < \lambda' < \sqrt{2}$. Let k be the unique natural number such that $(\lambda')^{2^k} \in [\sqrt{2}, 2)$. Remark 3.5 implies that w has a k th renormalization w_0 , and z^{2^k} is a root of P_{w_0} . Using w_0 in place of w in the argument in the previous paragraph, we get a critically periodic growth rate λ_4 close to $(\lambda')^{2^k}$, such that one of its Galois conjugates z_2 is close to z^{2^k} . The conclusion in Proposition 4.2 further implies that any (2^k) th root of z_2 must be a Galois conjugate of the (2^k) th root of λ_4 as well, which implies that there is a Galois conjugate of $\lambda_4^{2^{-k}}$ which is close to z , which finishes the proof of the proposition. □

The following corollary is not used to prove any further results in the present work.

COROLLARY 4.7. *Let V denote the set of all real numbers $\lambda \in (1, 2)$ such that:*

- (1) *the tent map f_λ is critically periodic;*
- (2) *there exists a word w such that $\text{It}_\lambda = w^\infty$;*
- (3) *the Parry polynomial $P_w(z)$ can be written as the product of an irreducible polynomial (in $\mathbb{Z}[z]$) and some cyclotomic polynomials.*

Then V is dense in $[1, 2]$.

Proof. The growth rates λ_3 , as well as the growth rates $\lambda_3^{2^{-k}}$, $k \in \mathbb{N}$, constructed in the proof of Theorem 4.5 all satisfy conditions (1)–(3). □

5. λ -suitability

In this section, we establish some basic properties of λ -suitability and prove the technical lemmas about λ -suitability that we will need in §6.

For convenience, we reproduce the definition of λ -suitability here. For $\lambda \in (1, 2)$, a sequence w is called λ -suitable if for every $\lambda' \in (\lambda, 2]$, the following conditions hold.

- (1) $\text{Rev}(\text{Pre}_n(w)) \leq_E \text{Pre}_n(\text{It}_{\lambda'})$ for all $n \in \mathbb{N}$.
- (2) If $\text{Rev}(\text{Pre}_n(w)) = \text{Pre}_n(\text{It}_{\lambda'})$, then the cumulative sign $s(\text{Pre}_n(w)) = -1$.
- (3) If $\text{It}_{\lambda'} = 1 \cdot 0^k \cdot 1 \dots$, $k \in \mathbb{N}$, then w does not contain $k + 1$ consecutive 0s (that is, if $\text{It}_{\lambda'}$ starts with 1 followed by k 0s and then 1, writing w as $w = w_1w_2 \dots$, there does not exist $n \in \mathbb{N}$ such that $w_i = 0$ for all $n \leq i \leq n + k$).
- (4) If $n \in \mathbb{N}$ satisfies $\sqrt{2} \leq_E (\lambda')^{2^n} < 2$, then $w = \mathcal{D}^n(w')$ for some sequence w' , where \mathcal{D}' is the map that replaces 0 with 11 and 1 with 01. Furthermore, if

$$\text{It}_{\lambda'^{2^n}} = 1 \cdot 0^k \cdot 1 \dots,$$

then w' does not contain $k + 1$ consecutive 0s.

The intuition behind the definition of λ -suitability is that we need a condition on sequences w so that Lemma 5.7 works.

Remark 5.1. An immediate consequence of monotonicity (Corollary 2.4) is that if λ' satisfies conditions (1)–(4) of Definition 1.5 for a sequence w , then so does every $\lambda'' > \lambda'$.

Remark 5.2. Every itinerary $\text{It}_{\lambda'}$ is admissible (by Theorem 2.2), so the admissibility condition implies that if $\text{It}_{\lambda'} = 1 \cdot 0^k \cdot 1 \dots$, then $\text{It}_{\lambda'}$ does not contain $k + 1$ consecutive 0s.

Remark 5.3. Note that the map \mathcal{D}' defined in the definition of λ -suitability is related to the doubling map \mathcal{D} by

$$\text{Rev} \circ \text{Pre}_{2n} \circ \mathcal{D} = \mathcal{D}' \circ \text{Rev} \circ \text{Pre}_n(w)$$

for every sequence w and $n \in \mathbb{N}$. (Recall that \mathcal{D} is replacing 0 with 11, 1 with 10, while \mathcal{D}' is replacing 0 with 11, 1 with 01.)

LEMMA 5.4. *The set of λ -suitable sequences is closed.*

Proof. We will show that the set of all sequences that are not λ -suitable is open. To do this, it suffices to show that given any sequence w which is not λ -suitable, we can find a

prefix of w such that every sequence that shares this prefix is not λ -suitable. It is clear that conditions (1) and (2) are closed conditions. For condition (3), we choose the prefix to be one that contains the first $k + 1$ consecutive 0s. Condition (4) is similar. \square

The following lemma is immediate because the definition of λ -suitability is of the form 'for all $\lambda' > \lambda$, $P(w, \lambda')$,' where P is a predicate.

LEMMA 5.5. *Let \mathcal{M}_λ denote the set of λ -suitable sequences. Then,*

$$\mathcal{M}_\lambda = \bigcap_{\lambda'' \in (\lambda, 2]} \mathcal{M}_{\lambda''}.$$

LEMMA 5.6. *If w is an admissible word that satisfies $w^\infty \leq_E \text{It}_\lambda$ for $\lambda \in (1, 2)$, then $(\text{Rev}(w))^\infty$ is λ -suitable.*

Proof. Observe that for any $n \in \mathbb{N}$, if we pick some $k \in \mathbb{N}$ such that $n + k$ is some multiple of $|w|$, then we have

$$\text{Rev}(\text{Pre}_n(\text{Rev}(w)^\infty)) = \text{Pre}_n(\sigma^k(w^\infty)). \tag{5.1}$$

Since w is admissible, $\text{Pre}_n(\sigma^k(w^\infty)) \leq_E \text{Pre}_n(w^\infty)$ for all $k, n \in \mathbb{N}$. By Corollary 2.4, for any $\lambda' > \lambda$,

$$\text{It}_\lambda <_E \text{It}_{\lambda'}. \tag{5.2}$$

We thus have that for any $n \in \mathbb{N}$,

$$\text{Rev}(\text{Pre}_n(\text{Rev}(w)^\infty)) = \text{Pre}_n(\sigma^k(w^\infty)) \leq_E \text{Pre}_n(w^\infty) \leq_E \text{Pre}_n(\text{It}_\lambda) \leq_E \text{Pre}_n(\text{It}_{\lambda'}),$$

which is condition (1) of the definition of λ -suitability.

Now suppose that for some $\lambda' > \lambda$,

$$\text{Rev}(\text{Pre}_n(\text{Rev}(w)^\infty)) = \text{Pre}_n(\text{It}_{\lambda'})$$

and $\text{Pre}_n(\text{It}_{\lambda'})$ has a positive cumulative sign. Then from (5.1), we have

$$\text{Pre}_n(\sigma^k(w^\infty)) = \text{Pre}_n(\text{It}_{\lambda'}).$$

Admissibility of w and (5.2) together imply that

$$\sigma^k(w^\infty) \leq_E w^\infty <_E \text{It}_{\lambda'}. \tag{5.3}$$

Because $\text{Pre}_n(\text{It}_{\lambda'})$ is the common prefix of $\sigma^k(w^\infty)$ and $\text{It}_{\lambda'}$, (5.3) implies it must also be a prefix of w^∞ . Removing this common n -prefix with positive cumulative sign from both sides of the inequality (by applying σ^n) yields

$$w^\infty \leq_E \sigma^n(w^\infty).$$

However, admissibility also implies that $\sigma^n(w^\infty) \leq w^\infty$, so in fact

$$w^\infty = \sigma^n(w^\infty).$$

Therefore,

$$w^\infty = (\text{Pre}_n(\text{It}_{\lambda'}))^\infty. \tag{5.4}$$

Let j be the index of the first place w^∞ differs from $\text{It}_{\lambda'}$. Clearly, $j > n$. Pick $m \in \mathbb{N}$ such that $mn < j \leq (m + 1)n$. Then, after removing the common prefix of length mn and positive cumulative sign from both w^∞ and $\text{It}_{\lambda'}$, we get from (5.4) and (5.2) that

$$\sigma^{mn}(w^\infty) = w^\infty <_E \text{It}_{\lambda'},$$

and hence,

$$\text{Pre}_n(\text{It}_{\lambda'}) = \text{Pre}_n(w^\infty) <_E \text{Pre}_n(\sigma^{mn}(\text{It}_{\lambda'})),$$

which contradicts with the fact that $\text{It}_{\lambda'}$ is admissible (by Theorem 2.2). Thus, condition (2) of the definition of λ -suitability holds.

Now condition (3) of the definition of λ -suitability follows from the assumption that $w^\infty \leq_E \text{It}_\lambda$.

For condition (4), suppose for some $\lambda' > \lambda$, $\sqrt{2} \leq (\lambda')^{2^n} < 2$. Then $\lambda^{2^n} < 2$, so by Lemma 3.4, $w = \mathfrak{D}^n(w')$ for some w' . Hence,

$$(\text{Rev}(w))^\infty = (\mathfrak{D}^n(\text{Rev}(w')))^\infty.$$

Because \mathfrak{D} preserves \leq_E and sends itineraries to itineraries (Lemma 3.2), the number of consecutive 0s in $(\text{Rev}(w'))^\infty$, which is the number of consecutive 0s in w'^∞ , cannot be more than the number of consecutive 0s in $\text{It}_{\lambda^{2^n}}$. □

The key combinatorial result we need to prove Theorem 1.7 is the following.

LEMMA 5.7. *Fix $\lambda \in [1, 2)$ and let w_0 be a finite dominant word such that $\text{It}_{\lambda'} \leq_E w_0^\infty$ for some $\lambda' > \lambda$. Let α be a word such that α :*

- (1) *ends with 1;*
- (2) *is a prefix of some λ -suitable sequence;*
- (3) *has positive cumulative sign; and*
- (4) $|w_0| > |\alpha|$.

Then the word $w_0 \cdot \text{Rev}(\alpha)$ is admissible.

Proof. Let $\alpha' = \text{Rev}(\alpha)$. It suffices to show that the admissibility criterion

$$\sigma^k((w_0\alpha')^\infty) \leq_E (w_0\alpha')^\infty$$

holds for all $1 \leq k < |\alpha| + |w_0|$.

Case 1: $k < |w_0|$. This implies that the comparison between $\sigma^k((w_0\alpha')^\infty)$ and $(w_0\alpha')^\infty$ is equivalent to the comparison of a proper suffix of w_0 concatenated with 1 with a prefix of w_0 of the same length. Hence,

$$\sigma^k((w_0\alpha')^\infty) \leq_E (w_0\alpha')^\infty$$

because w_0 is dominant.

Case 2: $|w_0| \leq k < |\alpha| + |w_0|$. Suppose the first place $\sigma^k((w_0\alpha')^\infty)$ and $(w_0\alpha')^\infty$ differ is at the j th position. It is evident that $1 \leq j \leq |\alpha| + |w_0|$. We divide this into two subcases.

Case 2A: $j \leq |w_0| + |\alpha| - k$. The fact that $|w_0| > |\alpha|$ and $k \geq |w_0|$ implies that $j \leq |w_0|$. Hence, the comparison between $\sigma^k((w_0\alpha')^\infty)$ and $(w_0\alpha')^\infty$ is equivalent to the comparison of a proper suffix of α' with a prefix of w_0 . Hence, item (1) of Definition 1.5 gives us

$$\sigma^k((w_0\alpha')^\infty) \leq_E (w_0\alpha')^\infty.$$

Case 2B: $j > |w_0| + |\alpha| - k$. The word $\beta := \text{Suf}_{|w_0|+|\alpha|-k}(\alpha')$, which is a common prefix of $\sigma^k((w_0\alpha')^\infty)$ and $(w_0\alpha')^\infty$, is identical to a prefix of w_0 , which is \geq_E than a prefix of $\text{It}_{\lambda'}$ for some $\lambda' > \lambda$. Hence, due to item (2) of Definition 1.5, β has a negative cumulative sign. Now, using the conclusion of Case 1, we have

$$\sigma_k^{|w_0|+|\alpha|-k}(\sigma^k((w_0\alpha')^\infty)) = (w_0\alpha')^\infty >_E \sigma_k^{|w_0|+|\alpha|-k}((w_0\alpha')^\infty).$$

Hence,

$$\sigma^k((w_0\alpha')^\infty) \leq_E (w_0\alpha')^\infty$$

because β has a negative cumulative sign. □

LEMMA 5.8. *Let w and w' be sequences, and let $\lambda \in (1, 2)$ and $k \in \mathbb{N}$ satisfy $\sqrt{2} \leq \lambda^{2^k} < 2$. If w is λ -suitable and $w = \mathfrak{D}^k(w')$, then w' is λ^{2^k} -suitable.*

Proof. By induction, we only need to prove it for $k = 1$. Assume $w = \mathfrak{D}'(w')$ is λ -suitable, we will now show that w' satisfies conditions (1)–(4) of Definition 1.5. By definition,

$$\text{Rev}(\mathfrak{D}'(v)) = \mathfrak{D}(\text{Rev}(v))$$

for any word v , so for any $\lambda' > \lambda$,

$$\begin{aligned} \text{Rev}(\text{Pre}_{2n}(\mathfrak{D}'(w'))) &= \text{Rev}(\mathfrak{D}'(\text{Pre}_n(w'))) \\ &= \mathfrak{D}(\text{Rev}(\text{Pre}_n(w'))) \leq \text{Pre}_{2n}(\text{It}_{\lambda'}) = \mathfrak{D}(\text{Pre}_n(\text{It}_{\lambda^2})). \end{aligned}$$

Hence condition (1) is true for w' because of Lemmas 3.1 and 3.2. Condition (2) of Definition 1.5 can be verified similarly. It is easy to see that w satisfies condition (4) implies that w' satisfies condition (4). Lastly, we will now show that w satisfies condition (4) will imply w' satisfies condition (3): if $\lambda^2 \geq \sqrt{2}$, this follows from the statement of condition (4). If $\lambda^2 < \sqrt{2}$, condition (4) implies that $w' = \mathfrak{D}'(w'')$ for some w'' , which implies that w' can never have more than one consecutive 0, and hence it also satisfies condition (3). □

6. Characterization inside the unit cylinder

LEMMA 6.1. *Let \mathcal{K} denote the space of compact subsets of \mathbb{R}^3 with the Hausdorff metric topology. Given any compact subset K of \mathcal{K} , the union of the elements of K is a compact subset of \mathbb{R}^3 .*

Proof. First, we claim there exists $R > 0$ such that $k \subset \overline{B_R(0)}$ for all $k \in K$. If this was not the case, then there exist k_1 and k_2 in K such that $d_{\text{Haus}}(k_1, k_2)$ is arbitrarily large, contradicting the fact that K is compact. Thus the claim is true.

Consider $K \times \overline{B_R(0)}$. As a product of compact sets, it is compact. Consider the subset $C \subseteq K \times \overline{B_R(0)}$ such that C consists of all pairs (k, x) such that $x \in k$. We claim C is closed, and thus as a closed subset of a compact set, C is compact. To see this, we will show that C is sequentially closed, that is, if (k_i, x_i) is a sequence in C converging to $(k_\infty, x_\infty) \in K \times \overline{B_R(0)}$, then $(k_\infty, x_\infty) \in C$. We have that $k_i \rightarrow k_\infty$ and $x_i \rightarrow x_\infty$, so suppose $x_\infty \notin k_\infty$. Since k_∞ is a compact set, $x \notin k_\infty$ implies there exists $\epsilon > 0$ such that $B_\epsilon(x)$ is contained in the complement of k_∞ . This implies that $\liminf d_{\text{Haus}}(k_i, k_\infty) \geq \epsilon$, contradicting the fact that $k_i \rightarrow k_\infty$ in the Hausdorff metric. So we have a continuous map from C to \mathbb{R}^3 sending (k, x) to x . The image under this map is compact. \square

The following two lemmas, which we state without proof, are immediate consequences of Rouché’s theorem.

LEMMA 6.2. *Let $M > 0$ be some fixed number. Let A be the set of power series with coefficients bounded by M equipped with the product topology. Let \mathcal{C} be the set of compact subsets of \mathbb{C} equipped with the Hausdorff topology. Then the map $\rho : A \rightarrow \mathcal{C}$ defined by*

$$\rho(f) = S^1 \cup \{z \in \mathbb{D} : f(z) = 0\}$$

is continuous.

LEMMA 6.3. *Fix real numbers $M > 0$, $0 < r < 1$, $\epsilon > 0$. Suppose α is a power series whose coefficients are all bounded in absolute value by M . Then there exists a real number $N = N(\alpha, r, \epsilon, M)$ such that for every power series β , whose coefficients are all bounded in absolute value by M and whose first N terms equal the first N terms of α , for each root z of α with $|z| < r$, there exists a root z' of β such that $|z - z'| < \epsilon$.*

Now we prove the first main theorem.

Proof of Theorem 1.7. For the reader’s convenience, we reproduce here the statement of Theorem 1.7. For any $\lambda \in (1, 2]$,

$$\Xi_\lambda \cap \overline{\mathbb{D}} = S^1 \cup \{z \in \mathbb{D} : G(w, z) = 1 \text{ for some } \lambda\text{-suitable sequence } w\}.$$

By Remark 1.11, the result holds for $\lambda = 2$. So fix $\lambda \in (1, 2)$. For brevity, let

$$Z_\lambda := \{z \in \mathbb{D} : G(w, z) = 1 \text{ for some } \lambda\text{-suitable sequence } w\}.$$

First, we show that $S^1 \cup Z_\lambda$ is compact. For each sequence w , the function from \mathbb{D} to \mathbb{C} given by $z \mapsto G(w, \cdot) - 1$ is a power series with bounded coefficients. Furthermore, the map from the set of sequences w (with the product topology) to the set of power series (with the product topology on coefficients) given by $w \mapsto G(w, \cdot) - 1$ is continuous. Therefore,

Lemma 6.2 implies that the map ρ from the set of sequences with the product topology to \mathcal{C} , the set of compact subsets of \mathbb{C} with the Hausdorff topology, given by

$$\rho(w) = S^1 \cup \{z \in \mathbb{D} : G(w, z) = 1\},$$

is continuous. By Lemma 5.4, the set of all λ -suitable sequences is closed (in the product topology on the set of sequences), and hence compact. Therefore, since ρ is continuous,

$$\{\rho(w) : w \text{ is } \lambda\text{-suitable}\}$$

is a compact subset of \mathcal{C} . Hence, Lemma 6.1 implies that

$$\bigcup_{w \text{ is } \lambda\text{-suitable}} \rho(w)$$

is compact. However, this set is precisely $S^1 \cup Z_\lambda$, so we have shown $S^1 \cup Z_\lambda$ is compact for any $\lambda \in [1, 2]$.

Next, we show that

$$\mathfrak{E}_\lambda \cap \overline{\mathbb{D}} \subseteq S^1 \cup Z_\lambda.$$

Theorem 4.5 shows that

$$\mathfrak{E}_\lambda \cap \overline{\mathbb{D}} = \bigcap_{\lambda' > \lambda} Y_{\lambda'}, \tag{6.1}$$

where $Y_{\lambda'}$ is defined to be the closure of the set of roots in $\overline{\mathbb{D}}$ of all Parry polynomials P_w such that w is admissible and $w^\infty \leq_E \text{It}_{\lambda'}$, union with S^1 . For each such w , let w_r be the sequence

$$w_r := (\text{Rev}(w))^\infty.$$

So fix $\lambda' > \lambda$ and consider any admissible word w such that $w^\infty \leq_E \text{It}_{\lambda'}$. By Lemma 2.1,

$$P_w(z) = (1 - z^{|w|})G(w_r, z).$$

By Lemma 5.6, w_r is λ' -suitable. Hence, all roots in $\overline{\mathbb{D}}$ of P_w are in $S^1 \cup Z_{\lambda'}$. Then, since $Z_{\lambda'}$ is closed, we have that

$$Y_{\lambda'} \subseteq S^1 \cup Z_{\lambda'}. \tag{6.2}$$

Now, combining (6.1) and (6.2) shows that for any point $z \in \mathfrak{E}_\lambda \cap \overline{\mathbb{D}}$, for each $n \in \mathbb{N}$, there exists a $(\lambda + 1/n)$ -suitable sequence v_n such that $G(v_n, z) = 1$. Let v_∞ be an accumulation point of the set $\{v_n : n \in \mathbb{N}\}$. By Lemma 5.5, the sequence v_∞ is λ -suitable. The continuity of $w \mapsto G(w, \cdot)$ implies that $G(v_\infty, z) = 1$. Hence, $\mathfrak{E}_\lambda \cap \overline{\mathbb{D}} \subseteq S^1 \cup Z_\lambda$.

Lastly, we show that $S^1 \cup Z_\lambda \subseteq \mathfrak{E}_\lambda \cap \overline{\mathbb{D}}$. We know from [BDLW19] that $S^1 \times [1, 2] \subset \Upsilon_2^{cp}$. Thus, $S^1 \subset \mathfrak{E}_\lambda$, so it suffices to show that $Z_\lambda \subset \mathfrak{E}_\lambda$. Fix a point $z \in Z_\lambda$ and let w be a λ -suitable sequence such that $G(w, z) = 1$. By condition (4) of Definition 1.5, there exists a sequence w' such that $w = \mathcal{D}'^k(w')$, and by Lemma 5.8, w' is λ^{2^k} -suitable and $\lambda^{2^k} \geq \sqrt{2}$. In particular, if $\lambda \geq \sqrt{2}$, we can let $k = 0$ and $w' = w$. As a consequence, there are infinitely many prefixes of w' that end with 1 and have a positive cumulative sign.

For any $m \in \mathbb{N}$ such that $\text{Pre}_m(w')$ has a positive cumulative sign and any word w'' with a positive cumulative sign, it follows immediately from the definitions of a Parry polynomial and of G that the first m terms of the power series $G(w', z) - 1$ and $P_{w'' \cdot \text{Rev}(\text{Pre}_m(w'))}(z)$ agree. Therefore, for any fixed $\epsilon_1 > 0$, by Lemma 6.3, there exists $N \in \mathbb{N}$ such that $\text{Pre}_N(w')$ ends with 1 and has a positive cumulative sign, and for any word w'' with a positive cumulative sign, there exists a point $z' \in B_{\epsilon_1}(z^{2^k})$ such that

$$P_{w'' \cdot \text{Rev}(\text{Pre}_N(w'))}(z') = 0. \tag{6.3}$$

For any fixed λ' satisfying $2 > \lambda' > \lambda^{2^k}$, pick a critically periodic growth rate $\lambda'' \in (\lambda^{2^k}, \lambda')$ and word w_0 with a positive cumulative sign such that $\text{It}_{\lambda''} = w_0^\infty$. Since $\lambda'' < \lambda'$, for sufficiently large n ,

$$w_0^n <_E \text{Pre}_{n|w_0|}(\text{It}_{\lambda'}).$$

Hence, by Proposition 2.5, there exists $n \in \mathbb{N}$ and a word w'_1 such that the word

$$w_1 := w_0^n w'_1$$

is dominant, $|w_1| > |w'|$, and

$$w_1 <_E \text{Pre}_{|w_1|}(\text{It}_{\lambda'}). \tag{6.4}$$

By Lemma 5.7,

$$w_1 \cdot \text{Rev}(\text{Pre}_N(w))'$$

is admissible. By (6.3),

$$P_{w_1 \cdot \text{Rev}(\text{Pre}_N(w'))}$$

has a root within distance ϵ_1 of z^{2^k} . By (6.4),

$$(w_1 \cdot \text{Rev}(\text{Pre}_N(w')))^{\infty} <_E \text{It}_{\lambda'}.$$

Hence, the k th doubling of $w_1 \cdot \text{Rev}(\text{Pre}_N(w'))$, denoted as w_d , satisfies

$$w_d^\infty <_E \text{It}_{(\lambda')^{1/2^k}}$$

and P_{w_d} has leading root in $[\lambda, (\lambda')^{1/2^k}]$ and a root in $B_{\epsilon'_1}(z)$, where ϵ'_1 is the diameter of the preimage of $B_{\epsilon_1}(z^{2^k})$ under the map $z \mapsto z^{2^k}$.

Now, since $\epsilon_1 > 0$ and $\lambda' > \lambda$ were arbitrary, and since Υ_2^{cp} is closed, we obtain that $(z, \lambda) \in \Upsilon_2^{cp}$, and hence $z \in \Xi_\lambda$. □

7. Characterization outside the unit cylinder

The goal of this section is to prove Theorem 1.8, a characterization of the part of the Master Teapot that is outside the unit cylinder.

Proof of Theorem 1.8. For any $\lambda \in (1, 2)$, denote by f_λ the λ -tent map, and define the set

$$R_\lambda := \begin{cases} \{z \in \mathbb{C} \setminus \overline{\mathbb{D}} : H(\text{It}_\lambda, z) = 0\} & \text{if } f_\lambda \text{ is not critically periodic,} \\ \{z \in \mathbb{C} \setminus \overline{\mathbb{D}} : H(\text{It}_\lambda, z) = 0 \text{ or } z^p = 2\} & \text{if } f_\lambda \text{ is critically periodic with period } p. \end{cases}$$

Next, define

$$R := \bigcup_{\lambda \in (1,2)} ((R_\lambda \cup S^1) \times \{\lambda\}).$$

We will show that

$$R = \Upsilon_2^{cp} \cap (\{z : |z| \geq 1\} \times (1, 2)).$$

Our argument will almost immediately follow from results in [Tio18], though these results must be translated from the context of the Mandelbrot set to the context of tent maps. The Milnor–Thurston kneading theory [MT88] yields an entropy-preserving semiconjugacy from the set of real quadratic polynomials f_c , $c \in [-2, 1/4]$, to the set of tent maps. If the quadratic f_c is sent by this semiconjugacy to a tent map f_λ , then $(1 - z^{-1})K_c(z^{-1}) = H(\text{It}_\lambda, z)$, and hence the roots (in \mathbb{D}) of the kneading determinant K_c coincide with the reciprocals of the roots (in $\mathbb{C} \setminus \overline{\mathbb{D}}$) of $H(\text{It}_\lambda, z)$. By [Jun14, Theorem 4.7], on the real slice of the Mandelbrot set, core entropy of $f_c : z \mapsto z^2 + c$ is strictly increasing except on ‘small Mandelbrot sets,’ where the core entropy is constant. Consequently, the entropy-preserving semiconjugacy from real quadratics to tent maps is injective except for collapsing each small Mandelbrot set to a single tent map. Furthermore, the semiconjugacy induces a surjection from the set of critically periodic quadratics f_c to the set of critically periodic tent maps, and each small Mandelbrot set contains a critically periodic quadratic.

We will first show that R is a (relatively) closed subset of $\mathbb{C} \times (1, 2)$. By Proposition 3.3 of [Tio18], the set that is the union of S^1 and the roots of K_c varies continuously in the Hausdorff topology with the parameter c . Consequently, when f_λ is not critically periodic, the function $s \mapsto R_s \cup S^1$ is continuous at $s = \lambda$. As stated in the proof of Theorem 7.1 of [Tio18], if (c_1, c_0) is the real section of a small Mandelbrot set of period p , then $K_{c_0}(t) = P_{c_0}(t)/(1 - t^p)$ and $K_{c_1}(t) = P_{c_0}(t)(1 - 2t^p)/(1 - t^p)$. Thus, in the Hausdorff topology,

$$\{z \in \mathbb{D} : K_{c_0}(z) = 0 \text{ or } z^p = \frac{1}{2}\} \cup S^1 = \lim_{c_* \nearrow c_1} \{z \in \mathbb{D} : K_{c_*}(z) = 0\} \cup S^1,$$

and so denoting by λ the growth rate of f_{c_0} , we have

$$\{z \in \mathbb{C} \setminus \overline{\mathbb{D}} : H(\text{It}_\lambda, z) = 0 \text{ or } z^p = 2\} \cup S^1 = \lim_{\lambda_* \searrow \lambda} \{z \in \mathbb{C} \setminus \overline{\mathbb{D}} : H(\text{It}_{\lambda_*}, z) = 0\} \cup S^1.$$

Therefore, for any λ for which the tent map f_λ is critically periodic,

$$R_\lambda \cup S^1 = \lim_{s \rightarrow \lambda_-} (R_s \cup S^1) \cup \lim_{s \rightarrow \lambda_+} (R_s \cup S^1).$$

Hence, R is a closed subset of $\mathbb{C} \times (1, 2)$.

When f_λ is critically periodic, $H(\text{It}_\lambda, z)$ can be written as a rational function with integer coefficients; consequently, R_λ contains all the Galois conjugates of λ in $\mathbb{C} \setminus \mathbb{D}$. Therefore, for every λ such that the tent map f_λ is critically periodic,

$$(\Xi_\lambda \setminus \mathbb{D}) \cup S^1 \subseteq R_\lambda \cup S^1.$$

Since $\Upsilon_2^{cp} \cap \{z \mid |z| \geq 1\} \times (1, 2)$ is formed by taking the closure of the union of all sets $(\Xi_\lambda \setminus \mathbb{D}) \cup S^1$ for λ critically periodic, and since R is already closed, this implies

$$\Upsilon_2^{cp} \cap (\{z \mid |z| \geq 1\} \times (1, 2)) \subseteq R.$$

To show containment in the other direction, Lemma 7.3 in [Tio18] implies that when f_λ is not critically periodic, $R_\lambda \times \{\lambda\} \subset \Upsilon_2^{cp}$. However,

$$\bigcup_{f_\lambda \text{ is not critically periodic}} (R_\lambda \cup S^1) \times \{\lambda\}$$

is dense in R , and hence $R \subset \Upsilon_2^{cp}$. □

8. Algorithms to test membership of Ξ_λ

In this section, we will describe an algorithm to check if a point $z_0 \in \mathbb{C}$ is in the complement of a slice Ξ_λ for $\lambda \in (1, 2)$.

First, if $\lambda < \sqrt{2}$, Theorems 1.7 and 1.8 imply that $z \in \Xi_\lambda$ if and only if $z^2 \in \Xi_{\lambda^2}$, so we can always reduce the question to the case $\lambda \in [\sqrt{2}, 2)$.

8.1. Testing z_0 with $|z_0| > 1$. When $|z_0| > 1$, Theorem 1.8 gives us a straightforward way to test if $z_0 \notin \Xi_\lambda$: calculating the first few terms of the power series $H(\text{It}_\lambda, z^{-1})$, then checking if z_0^{-1} is a root of this power series. More precisely, we have the following algorithm.

Algorithm 1: Algorithm to verify that $|z_0| > 1$ is not in Ξ_λ .

if The λ -tent map is critically periodic with period n , and $z_0^n = 2$ **then**
 $z_0 \in \Xi_\lambda$
else
 for $n > 1$ **do**
 Calculate $\text{Pre}_{n+1}(\text{It}_\lambda)$;
 Find the polynomial P_n which consists of the first n terms of power series $H(\text{It}_\lambda, z^{-1})$;
 If $|P_n(z_0^{-1})| > 2|z_0|^{-n}/(1 - |z_0|)$, **then** $z_0 \notin \Xi_\lambda$;

Remark 8.1. If instead of checking if $z_0 \notin \Xi_\lambda$, we want to see if an ϵ -neighborhood of z_0 is contained in the complement of Ξ_λ , we can change the last line of Algorithm 1 to make use of Rouché’s theorem.

8.2. Testing z_0 with $|z_0| < 1$. If $|z_0| < 1$, a way to certify that $z_0 \notin \Xi_\lambda$ is by first finding the set of all words of length N that satisfy conditions (1)–(3) of Definition 1.5 (condition (4) is trivial because $\lambda \geq \sqrt{2}$), denoted as $\mathcal{M}_{N,\lambda}$, for each word $w = (w_1 \dots w_N) \in \mathcal{M}_{N,\lambda}$, evaluating $f_{w_N, z_0}^{-1} \circ f_{w_{N-1}, z_0}^{-1} \dots \circ f_{w_1, z_0}^{-1}(1)$, and checking that they are all sufficiently large. More precisely, the algorithm can be described as follows.

Algorithm 2: Algorithm to verify that $|z_0| < 1$ is not in Ξ_λ , where $\lambda \in [\sqrt{2}, 2)$.

```

for  $N > 1$  do
    Let  $\mathcal{M}_{N,\lambda}$  be the set of all words of length  $N$  that satisfies conditions (1)–(3)
    in Definition 1.5;
    Let  $flag \leftarrow False$ ;
    for  $w \leftarrow (w_1 \dots w_N) \in \mathcal{M}_{N,\lambda}$  do
        if  $f_{w_N,z_0}^{-1} \circ f_{w_{N-1},z_0}^{-1} \dots \circ f_{w_1,z_0}^{-1}(1) \leq 2/(1 - |z_0|)$  then
             $flag \leftarrow True$ ;
            Break;
    If  $flag = False$ , then  $z_0 \notin \Xi_\lambda$ ;
```

Remark 8.2. In the definition of $\mathcal{M}_{N,\lambda}$ above, one needs to check conditions (1)–(3) in Definition 1.5 for all the $\lambda' > \lambda$. However, in practice, one does not really need to check these conditions for infinitely many λ' : instead, one can pick a decreasing sequence λ'_j converging to λ , then there must be some $j = j_0$ such that for any $i \leq N$, let f_s be the s -tent map, then $H_i(s) = f_s^{oi}(1)$ does not have any critical points in $(\lambda, \lambda'_{j_0})$. One can show that the N -prefix of $\text{It}_{\lambda'_j}$ for $j > j_0$ should be the same as the N -prefix of $\text{It}_{\lambda'_{j_0}}$, and in Definition 1.5, the only thing we ever used for $\text{It}_{\lambda'}$ is its N -prefix, so we can set $\lambda' = \lambda'_{j_0}$ and verify the three conditions in finite time.

The reason that Algorithm 2 is true is due to the following proposition.

PROPOSITION 8.3. *Let $\lambda \in [\sqrt{2}, 2)$, and let $\mathcal{M}_{N,\lambda}$ be defined as in Algorithm 2. Suppose $|z| < 1$, then $z \notin \Xi_\lambda$ if and only if there exists $N \in \mathbb{N}$ such that for every word $w = w_1 \dots w_N \in \mathcal{M}_{N,\lambda}$,*

$$f_{w_N,z}^{-1} \circ \dots \circ f_{w_1,z}^{-1}(1) \geq \frac{2}{1 - |z|} + \epsilon.$$

Proof. First, we assume that there is some N such that for every word $w = w_1 \dots w_N \in \mathcal{M}_{N,\lambda}$,

$$f_{w_N,z}^{-1} \circ \dots \circ f_{w_1,z}^{-1}(1) \geq \frac{2}{1 - |z|} + \epsilon$$

and prove that $z \notin \Xi_\lambda$. Suppose $z \in \Xi_\lambda$. Then by Theorem 1.7, there must be some λ -suitable sequence $v = v_1 v_2 \dots$ such that

$$1 = G(v, z) = \lim_{n \rightarrow \infty} f_{v_1,z} \circ \dots \circ f_{v_n,z}(1).$$

In other words, for any $\delta > 0$, there is some $n > N$ such that

$$|f_{v_1,z} \circ \dots \circ f_{v_n,z}(1) - 1| < \delta.$$

By the definition of $\mathcal{M}_{N,\lambda}$, the word $v_1 \dots v_N \in \mathcal{M}_N$. Let $u = f_{v_1,z} \circ \dots \circ f_{v_n,z}(1)$. Then, $|u - 1| < \delta$. Because $f_{v_N,z}^{-1} \circ \dots \circ f_{v_1,z}^{-1}$ is continuous, we can pick δ small enough such that

$$f_{v_N,z}^{-1} \circ \dots \circ f_{v_1,z}^{-1}(u) > \frac{2}{1 - |z|}.$$

However,

$$f_{v_N,z}^{-1} \circ \dots \circ f_{v_1,z}^{-1}(u) = f_{v_{N+1},z} \circ \dots \circ f_{v_n,z}(1).$$

By calculation, it is easy to verify that 1 is in the disc

$$D_{2/(1-|z|)} = \left\{ z \in \mathbb{C} : |z| \leq \frac{2}{1 - |z|} \right\},$$

and both $f_{0,z}$ and $f_{1,z}$ send $D_{2/(1-|z|)}$ to itself. Hence,

$$|f_{v_{N+1},z} \circ \dots \circ f_{v_n,z}(1)| \leq \frac{2}{1 - |z|},$$

which is a contradiction.

Now, for the other direction, we assume that for any $N \in \mathbb{N}$, there is some word $w = w_1 \dots w_N \in \mathcal{M}_{N,\lambda}$ such that

$$f_{w_N,z}^{-1} \circ \dots \circ f_{w_1,z}^{-1}(1) \leq \frac{2}{1 - |z|}$$

and prove that $z \notin \Xi_\lambda$. Let C_N be the set of sequences such that an N -prefix of it is in $\mathcal{M}_{N,\lambda}$, and this N prefix is of the form $w_1 \dots w_N$ such that

$$f_{w_N,z}^{-1} \circ f_{w_{N-1},z}^{-1} \dots f_{w_1,z}^{-1}(1) \leq \frac{2}{1 - |z|}.$$

The fact that $f_{0,z}$ and $f_{1,z}$ both send $D_{2/(1-|z|)}$ to itself implies that $C_{N+1} \subset C_N$, and all these sets are non-empty and compact under the product topology, and hence their intersection is non-empty. Let $w \in \bigcap_N C_N$, then w is λ -suitable and it is easy to see that $G(w, z) = 1$. □

Furthermore, we have an effective version of the Proposition 8.3 above.

PROPOSITION 8.4. *Let λ, z, N , and ϵ be as in Proposition 8.3 above, $\frac{1}{2} < |z| < 1$. Then for any $y \in \mathbb{C}$, if*

$$|y - z| < \min \left\{ \frac{1 - |z|}{2}, \frac{(1 - |z|)^2 \epsilon}{16}, |z| - \frac{1}{2}, \frac{\epsilon}{N \cdot 2^{N+1}} \right\},$$

then $y \notin \Xi_\lambda$.

Remark 8.5. The assumption $|z| > \frac{1}{2}$ is a reasonable one because it is well known (cf. [Tio18]) that if $|z| < \frac{1}{2}$, then $z \notin \Xi_\lambda$ for any $\lambda \in (1, 2)$.

Proof. It is easy to see that as long as $|y| < 1$,

$$\left| \frac{2}{1 - |z|} - \frac{2}{1 - |y|} \right| < \epsilon/2,$$

and for any $w = w_1 \dots w_N \in \mathcal{M}_{N,\lambda}$,

$$|f_{w_N,z}^{-1} \circ f_{w_{N-1},z}^{-1} \dots f_{w_1,z}^{-1}(1) - f_{w_N,y}^{-1} \circ f_{w_{N-1},y}^{-1} \dots f_{w_1,y}^{-1}(1)| < \epsilon/2,$$

then y also satisfies the assumption in Proposition 8.3. The first condition, $|y| < 1$, holds because $|y - z| < (1 - |z|)/2$, which implies $|y| < (1 + |z|)/2 < 1$. The second condition,

$$\left| \frac{2}{1 - |z|} - \frac{2}{1 - |y|} \right| < \epsilon/2,$$

holds because $|y| < (1 + |z|)/2$ and $|y - z| < (1 - |z|)^2\epsilon/16$. The third condition,

$$|f_{w_N,z}^{-1} \circ f_{w_{N-1},z}^{-1} \cdots f_{w_1,z}^{-1}(1) - f_{w_N,y}^{-1} \circ f_{w_{N-1},y}^{-1} \cdots f_{w_1,y}^{-1}(1)| < \epsilon/2,$$

holds because of the following argument. As a polynomial of $1/z$,

$$f_{w_N,z}^{-1} \circ f_{w_{N-1},z}^{-1} \cdots f_{w_1,z}^{-1}(1)$$

has degree N and coefficients bounded between -2 and 2 , and hence has its derivative bounded by $N2^{N-1} \cdot 2 = N \cdot 2^N$ on the annulus $\{y \in \mathbb{C} : 1 \leq |y| \leq 2\}$. Because $|y - z| < |z| - \frac{1}{2}$, y is inside this annulus, so this third condition follows from the assumption that $|y - z| < \epsilon/N \cdot 2^{N+1}$ and the mean value theorem. \square

9. Asymmetry of Ξ_λ

The following proposition is likely well known to experts; we include the proof for completeness.

PROPOSITION 9.1. $\Omega_2^{cp} \cap \mathbb{D}$ is invariant under reflection across the real axis and across the imaginary axis.

Proof. The set $\Omega_2^{cp} \cap \mathbb{D}$ is invariant under reflection across the real axis because Galois conjugates come in complex conjugate pairs. Tiozzo [Tio18] showed that $\Omega_2^{cp} \cap \mathbb{D} \setminus S^1$ is the set of all the roots in \mathbb{D} of all power series with all coefficients in $\{\pm 1\}$. So if $z \in \mathbb{D}$ is a root of a power series S with coefficients in $\{\pm 1\}$, then $-z$ is a root of the power series formed from S by flipping the sign of the coefficients on all terms of odd degree. Therefore, the complex conjugate, $\overline{-z}$, is in Ω_2^{cp} . \square

However, our Algorithm 2 in the previous section can be used to show that $\Xi_\lambda \cap \mathbb{D}$ does not necessarily have such symmetry, which proves Theorem 1.14.

Proof of Theorem 1.14. We only need to show that there is some $z \in \Xi_{1.82} \cap \mathbb{D}$ such that $-z \notin \Xi_{1.82} \cap \mathbb{D}$. Consider the tent map with growth rate being the leading root of

$$-1 + z^2 - z^4 + z^6 - 2z^7 + 3z^8 - 4z^9 + 3z^{10} - 2z^{11} + z^{12} - 2z^{13} + z^{14},$$

which is approximately 1.8149185987640513 and is smaller than 1.82, and hence any Galois conjugate of this leading root must be in $\Xi_{1.82}$. Let z be the Galois conjugate near the point $-0.5840341196392905 + 0.4820600149798202i$. Applying Algorithm 2 to $-z$ for $N = 20$ shows that $-z \notin \Xi_{1.82}$. \square

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