

SOLENOIDAL ATTRACTORS WITH BOUNDED COMBINATORICS ARE SHY

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*Dedicated to the memory of
Wellington de Melo (1946-2016)*

ABSTRACT. We show that in a generic finite-dimensional real-analytic family of real-analytic multimodal maps, the subset of parameters on which the corresponding map has a solenoidal attractor with bounded combinatorics is a set with zero Lebesgue measure.

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1. INTRODUCTION.

A multimodal map $f: I \rightarrow I$ is a smooth map defined in an interval I , with a finite number of critical points c_i , all of them local maximum or local minimum, and such that $f(\partial I) \subset \partial I$. We are going to assume that f is real-analytic.

For *unimodal* maps with a *quadratic* critical point, the understanding of the *typical* behaviour is very satisfactory. Lyubich [26] and Graczyk and Świątek [18] proved the density of hyperbolic parameters in the quadratic family. But this was not enough to understand the typical behaviour at almost every parameter of the

Date: July 23, 2019.

2000 *Mathematics Subject Classification.* 37E05, 37E20, 37F25, 37C20, 37D20, 37E20, 37L45.

Key words and phrases. rigidity, renormalization, conjugacy, universality, hyperbolic, solenoidal attractor, multimodal.

We thank the referees for their careful reading and suggestions. D.S. was partially supported by CNPq-Brazil 430351/2018-6, 307617/2016-5, 470957/2006-9, 310964/2006-7, 472316/03-6, 303669/2009-8, 305537/2012-1 and São Paulo Research Foundation-FAPESP 03/03107-9, 2008/02841-4, 2010/08654-1, 2017/06463-3.

quadratic family. Indeed earlier Jakobson [20] proved that in the complement of the hyperbolic parameters there is a subset of parameters with positive measure for which the dynamics admits an absolutely continuous invariant probability (the map is stochastic). Finally Lyubich [29] proved that for almost every parameter in the quadratic family the map is either regular (a hyperbolic map) or stochastic. Avila, Lyubich and de Melo [3] generalised this result for a non degenerate real analytic family of quadratic real analytic unimodal maps and Avila and Moreira [5] improved this, proving that in a non degenerate family the map is either regular or Collet-Eckmann at almost every parameter. There are similar results for real-analytic unimodal maps with higher order by Clark [11]. See also Bruin, Shen and van Strien [10], Avila, Lyubich and Shen [4] and Shen [38] for related results.

Similar studies for multimodal maps (or even unimodal maps with higher order) pose new difficulties. New phenomena appear, as non-renormalizable maps without decay of geometry (see Bruin, Keller, Nowicki and van Strien [8], Keller and Nowicki [22]). Decay of geometry was an essential tool in the study of unimodal quadratic maps. This was a major difficulty in the study of the so-called Fibonacci renormalization for unimodal maps with higher order in Smania [42] and the proof of the density of hyperbolicity for polynomials in Kozlovski, Shen, van Strien [24] [23]. Moreover the lack of decay of geometry allows additional metric behaviours, as the existence of wild attractors. See Milnor [33], Bruin, Keller, Nowicki and van Strien [8] and Bruin, Keller and St. Pierre [9].

Another issue is that for families of polynomials with more than one critical point (as in the cubic family) the parameter space has dimension larger than one. That implies that the parapuzzle approach as used in the unimodal case (see Lyubich [28], Avila, Lyubich and de Melo [3]) does not seem to be easily adaptable here, since the fact that holomorphic maps with one-variable are conformal was used in a crucial way.

So as a consequence there are a lot of unanswered questions concerning the typical behaviour in the *measure-theoretical* sense in families of polynomials and/or multimodal maps.

One of them is how often maps with *solenoidal attractors* appear in these families. We say that a set $\Lambda \subset I$ is a *solenoidal attractor* of a multimodal map f if there exists an increasing sequence of positive integers n_k , $k \in \mathbb{N}$, and a family of closed intervals $I_j^k \subset I$, $k \in \mathbb{N}$ and $0 \leq j < n_k$, such that

- A. For each k the intervals in the family $\{I_j^k\}_{j < n_k}$ has pairwise disjoint interior.
- B. We have $f(I_j^k) \subset I_{j+1 \bmod n_k}^k$.
- C. For every k

$$\{c_i\}_i \cap \bigcup_{j < n_k} I_j^k \neq \emptyset.$$

and

$$\bigcup_{j < n_{k+1}} I_j^{k+1} \subset \bigcup_{j < n_k} I_j^k.$$

- D. We have

$$\Lambda = \bigcap_k \bigcup_{j < n_k} I_j^k.$$

See Blokh and Lyubich [6] [7] for more information on attractors for multimodal maps. The solenoidal attractor Λ has *bounded combinatorics* if

$$\sup_k \frac{n_{k+1}}{n_k} < \infty.$$

One important step in previous results about the typical behaviour in families of unimodal maps is to prove that at a typical parameter the map *does not* have solenoidal attractors. This was done in the quadratic family by Lyubich [28] and for no degenerate families of unimodal maps by Avila, Lyubich and de Melo [3]. An important tool in many of these results on unimodal maps is the fact that the topological classes of unimodal maps extend to an analytic, codimension one lamination (except a few combinatorial types). This implies that the holonomy of this lamination is quite regular. Our goal is to prove that

Theorem A. *On a generic real-analytic finite-dimensional family of real-analytic multimodal maps with quadratic critical points and negative schwarzian derivative the set of parameters whose corresponding maps have a solenoidal attractor with bounded combinatorics has zero Lebesgue measure.*

The precise statement is given in Theorem 7. We also have an analogous result for families with finite smoothness and continuous families. The method used in the unimodal case in Avila, Lyubich and de Melo [3] no longer works in the multimodal case, once the lamination of topological classes has higher codimension, so we are going to use a quite different approach. If a map f has a solenoidal attractor with bounded combinatorics, one can find an induced map F of f that is a composition of unimodal maps and it is infinitely renormalizable as defined in [40]. In particular the iterations of the *renormalization operator \mathcal{R} for multimodal maps* are well-defined for F . Using the universality property proved in [40] one can prove that F belongs to the stable lamination of the omega-limit set Ω of \mathcal{R} . The renormalization operator is a real-analytic, compact and non-linear operator acting on a Banach space of real analytic multimodal maps.

Our main technical result is that

Theorem B. *Consider the renormalization operator \mathcal{R} acting on real-analytic multimodal maps which are renormalizable with combinatorics bounded by some $p > 0$. Then the omega-limit set Ω of \mathcal{R} is a hyperbolic set.*

The precise statement is given in Section 5. Lyubich [27] proved the hyperbolicity of the omega-limit set in the unimodal case using the so-called Small Orbits Theorem. We use a different approach, reducing the study of the hyperbolicity of Ω to the study of the existence and regularity of solutions for a certain linear cohomological equation. This new method allows us to deal only with real-analytic maps and its complex analytic extensions.

The relationship between renormalization and cohomological equations appears in many contexts, as for instance in the study of rigidity of circle diffeomorphisms and generalized interval exchange transformations. Closer to our setting we have the introduction by Lyubich [27] of the concept of horizontal direction in the study of the renormalization operator for unimodal maps and the study of the hyperbolicity of the fixed point of the action of a pseudo-Anosov map on certain character variety by Kapovich [21].

The final ingredient is a very recent result on partially hyperbolic invariant sets on Banach spaces [43]. The result we use is, roughly speaking, the following (see [43, Theorem 1]). Suppose that a “regular” real-analytic operator \mathcal{R} has a hyperbolic

set Ω , and its stable lamination $W^s(\Omega)$ satisfies the “Transversal Empty Interior property”: every regular manifold M that is transversal to $W^s(\Omega)$ intersects $W^s(\Omega)$ in a subset of empty interior (in the topology of M). Then a generic real-analytic finite-dimensional family intersects $W^s(\Omega)$ on a subset with zero Lebesgue measure. This will give us our main result. The Transversal Empty Interior property for the renormalization operator (see Corollary 9.1) is closely related with the fact that maps F that are infinitely renormalizable with bounded combinatorics can be approximated by hyperbolic maps.

Some of the most classical families of one-dimensional dynamical systems are families of polynomials. The *cubic family* is the two parameter family

$$f_{a,b}(z) = z^3 - 3a^2z + b$$

The critical points of $f_{a,b}$ are $a, -a$. We also have

Theorem C. *The set of parameters $(a, b) \in \mathbb{R}^2$ such that $f_{a,b}$ is infinitely renormalizable with bounded combinatorics has zero 2-dimensional Lebesgue measure.*

The study of the renormalization operator has a long history. It was first discovered in the unimodal case by Feigenbaum [15][16] and Coullet and Tresser [45]. They conjectured that the period-doubling renormalization operator has a unique fixed point in a space of quadratic unimodal maps, that this fixed point is hyperbolic and its codimension one stable manifold contains all Feigenbaum maps. Such conjectures could explain certain intriguing universal features of the bifurcation diagram of families of unimodal maps. The existence and hyperbolicity of such fixed point was proven by Lanford [25]. Such conjectures were later extended for arbitrary bounded combinatorial types, when the fixed point need to be replaced by an omega-limit set that is hyperbolic (see Derrida, Gervois and Pomeau [14] and Gol’berg, Sinai and Khanin [17]). Sullivan [44] proved that the orbit by the renormalization operator of a map that is infinitely renormalizable with bounded combinatorics converges to the orbit of a map on the omega limit set and such orbit is determined by the combinatorics of the map. This Sullivan’s result in particular implies that uniqueness of the fixed point to the period-doubling renormalization operator and that it attracts all Feigenbaum maps. McMullen[32] proved that the rate of convergence is indeed exponential. Finally Lyubich [27] proved that the omega-limit set of the renormalization operator for unimodal maps is hyperbolic. In particular Lyubich found a suitable space where the renormalization operator is a complex-analytic non-linear operator. See also de Faria, de Melo and Pinto [12] for the proof of the conjectures in the C^r case.

The renormalization operator for bimodal maps was first considered in MacKay and van Zeijts [30] and Hu [19]. The general multimodal case, with a precise combinatorial description, was described in [39], as well the so-called real and complex a priori bounds for bounded combinatorics. In [41] it was proved the phase space universality in the bounded combinatorics case.

It is natural to ask if results as Theorems A., B. and C. holds for the full renormalization operator, that is, considering *unbounded* combinatorial type as well. We believe that recent results by Avila and Lyubich [2] on the contraction of the renormalization operator in the hybrid class of infinitely renormalizable unimodal maps with unbounded combinatorics can be carried out for multimodal maps. So

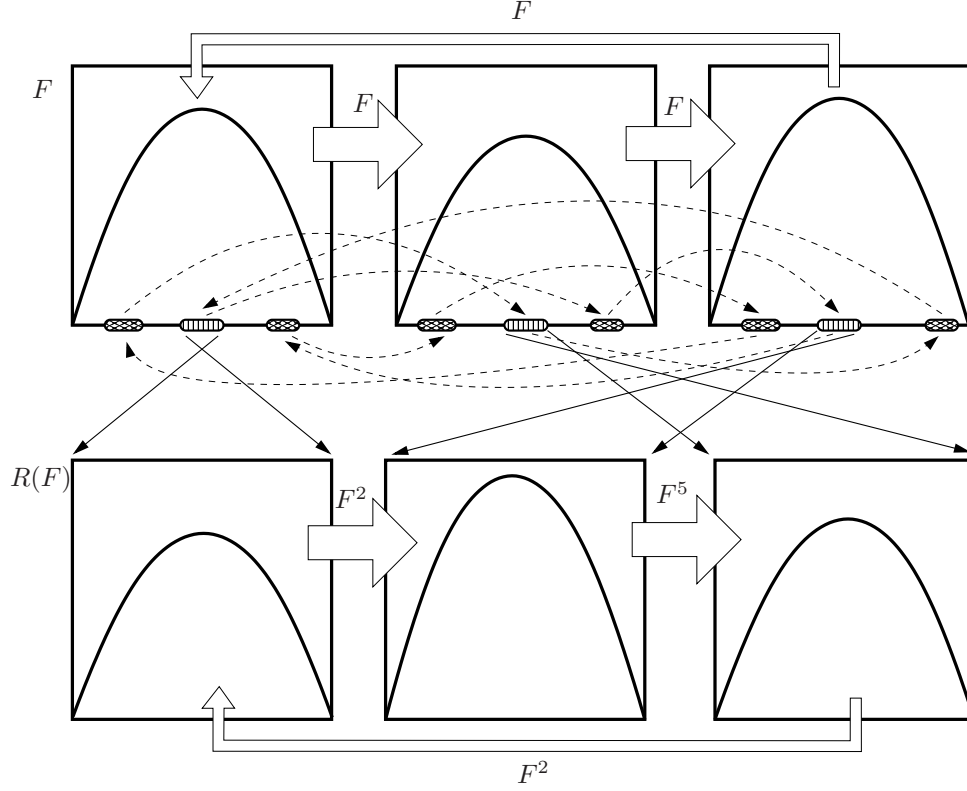


FIGURE 1. Renormalization of an extended map of type 3.

the main difficulty seems to be to understand the dynamics of the renormalization operator in the directions transversal to the horizontal spaces, as in the proof of Theorem B. New difficulties arise in the unbounded case, once the omega-limit set of the renormalization operator has not a simple structure anymore. However we are confident that a version of the Key Lemma (Theorem 4) can be obtained in this setting and it will be useful to understand the dynamics of the renormalization operator and the generic behavior in families of multimodal maps.

2. RENORMALIZATION OF EXTENDED MAPS.

To study the renormalisation of multimodal maps, it is more convenient to decompose the dynamics of f in its unimodal parts. Let $I_i = [-1, a_i]$, with $a_i > 0$, be intervals and

$$(1) \quad f_i: I_i \rightarrow I_{i+1 \bmod n}$$

be C^1 maps such that c_i is its unique critical point, that is a maximum and $f_i(\partial I_i) \subset \partial I_{i+1 \bmod n}$. An extended map F is defined by a finite sequence (f_1, \dots, f_n) of maps is the map defined on $I_F^n = \{(x, i): x \in I_i, 1 \leq i \leq n\}$ as

$$(2) \quad F(x, i) = (f_i(x), i + 1 \bmod n)$$

We say that f is a multimodal map of type n if it can be written as a composition of n unimodal maps: to be more precise, if there exist maps f_1, \dots, f_n as above satisfying

- (1) $f = f_n \circ \dots \circ f_1$.
- (2) We have $f_i(c_i) \geq c_{i+1 \bmod n}$.

The n -uple (f_1, \dots, f_n) is a decomposition of f . In this paper, we will assume that the unimodal maps are analytic and the critical points of f_i are quadratic. Clearly f has many decompositions.

In [39], we proved that deep renormalizations of infinitely renormalizable multimodal maps are multimodal maps of type n .

2.1. Renormalization of extended maps. We say that J is a k -periodic interval, $k \geq 2$, of the extended map F if

- $(c_1, 1) \in J$ ((c_i, i) are the critical points of F),
- $\{J, F(J), \dots, F^{k-1}(J)\}$ is a collection of intervals with disjoint interiors,
- The union of intervals in the above family contains $\{(c_i, i)\}$,
- $F^k(J) \subset J$.

We will call k the period of J . If F has a k -periodic interval, for some k , we say that F is renormalizable.

Suppose that there exists a k -periodic interval for F . Let $P \subset I_1 \times \{1\}$ be the maximal interval which is a k -periodic interval for F . Then $F^k(\partial P) \subset \partial P$. We say that P is a restrictive interval for F of period k . Note that if P and \tilde{P} are, respectively, restrictive intervals for F of period k and \tilde{k} , $k < \tilde{k}$, then $\tilde{P} \subset P$. Let P be a restrictive interval and let $0 = \ell_1 < \dots < \ell_n$ be the iterations such that $(c_i, i) \in F^{\ell_j}(P)$ for some i . Let P_j be the symmetrization of $F^{\ell_j}(P)$ in relation to (c_i, i) . Observe that P_j contains a periodic point in its boundary. If $(c_i, i) \in P_j$ Let

$$A_{P_j} : \mathbb{C} \times \{i\} \rightarrow \mathbb{C} \times \{j\}$$

be the affine map which maps (c_i, i) to $(0, j)$ and this periodic point to -1 . Let $[-1, b_j] \times \{j\} = A_{P_j}(P_j)$. Then

$$g_j : [-1, b_j] \times \{j\} \rightarrow [-1, b_{j+1}] \times \{j+1\}$$

defined by $g_j = A_{P_{j+1}} \circ F^{\ell_{j+1} - \ell_j} \circ A_{P_j}^{-1}$ is a unimodal map. The extended map $G(x, j) = g_j(x, j)$ is called a renormalization of the extended map F . An extended map may have many renormalizations, but at most one with a given period. The renormalization with minimal period k is called the first renormalization of F , and it is denoted $R(F)$.

Following the notation in [40], the primitive marked combinational data (primitive m.c.d) associated with the first renormalization of F is $\sigma = \langle A, \prec, A^c \rangle$ where

- $A = \{1, 2, \dots, k\}$,
- The relation \prec is a partial order on A defined in the following way $i \prec \ell$ if $F^i J$ and $F^\ell J$ belongs to the same interval in I_P^n and $F^i J$ is on the left side of $F^\ell J$,
- The set A^c is a subset of A and $i \in A^c$ if $F^i J$ intersects $\{(c_i, i)\}$.

The extended map $R(F)$ can be renormalizable again and so on. If this process can be continued indefinitely, we say that F is infinitely renormalizable. If F is infinitely renormalizable then all of its renormalizations can be obtained iterating

the operator R . Denote by P_0^k the restrictive interval associated to the k -th renormalization $R^k(F)$. If $q \in C(F) := \{(c_i, i)\}$, denote by the corresponding capital letter Q_0^k the symmetrization of the interval $F^\ell(P_0^k)$ which contains q . We reserve the letter p for $(c_1, 1)$. The critical point r for F will be the successor of the critical point q at level k if $r \in F^\ell(Q_0^k)$, for the minimal ℓ so that $F^\ell(Q_0^k)$ contains a critical point. Define $n_r^k = \ell$. Then, for any $r \in C(F)$, $k \in \mathbb{N}$ and $i < n_r^k$, there exists an interval R_{-i}^k so that

- F^i is monotone in R_{-i}^k ,
- $F^i(R_{-i}^k) = R_0^k$,
- The interval $F^{n_r^k-i}(Q_0^k)$ is contained in R_{-i}^k .

For details, see [39].

Denote by N_k the period of the restrictive interval P_0^k . We say that F has C -bounded combinatorics if $N_{k+1}/N_k \leq C$ for every k .

For $(x, i), (y, j) \in I_F^n$, we say that $(x, i) < (y, j)$ if $i = j$ and $x < y$. The intervals of I_F^n are the sets $J \times \{i\}$, for some interval $J \subset I_i$ and $1 \leq i \leq n$. If c_i is the critical point of f_i , denote $C(F) = \{(i, c_i)\}_i$.

Let F and G be two infinitely renormalizable extended maps. We say that F and G have same combinatorics if $F^i(c_k) < F^j(c_\ell)$ if and only if $G^i(c_k) < G^j(c_\ell)$, for any $i, j \geq 0$ and k and $\ell < n$.

Let σ_i be the primitive m.c.d. of the (first) renormalization of $R^i(F)$ and $\tilde{\sigma}_i$ be the primitive m.c.d. of the (first) renormalization of $R^i(G)$. It turns out that F and G has the same combinatorics if and only if $\sigma_i = \tilde{\sigma}_i$ for every i . So we say that F has combinatorics $(\sigma_1, \sigma_2, \sigma_3, \dots)$. Moreover, let $\mathcal{C}_{p,n}$ be the set of all primitive m.c.d. that appears as the first renormalization of an extended map with n intervals and it has period either smaller or equal to p . By Corollary 2.3 in [40] for every given sequence $\sigma_i \in \cup_p \mathcal{C}_{p,n}$, $i \geq 1$, there exists a real analytic extended map (with, say, quadratic critical points) whose i -th renormalization has primitive m.c.d. σ_i .

2.2. Polynomial-like extended maps. Denote $\mathbb{C}_n = \{(x, i) : x \in \mathbb{C}, 1 \leq i \leq n\}$ (in other words, \mathbb{C}_n is a disjoint union of n copies of \mathbb{C}). Given an open set $O \subset \mathbb{C}_n$, denote

$$O_i = O \cap (\mathbb{C} \times \{i\}).$$

A polynomial-like extended map is a map $F : U \rightarrow V$, where

- U and V are open sets of \mathbb{C}_n , where $\overline{U} \subset V$,
- for each i , $F(U_i) = V_{i+1 \bmod n}$. Moreover $F : U_i \rightarrow V_{i+1 \bmod n}$ is a proper map with a unique critical point.
- for each i we have that U_i and V_i are simply connected domains.

We define

$$\text{mod}(V \setminus U) = \min_i \text{mod}(V_i \setminus U_i).$$

The filled-in Julia set $K(F)$ of a polynomial-like extended map F is defined as

$$K(F) = \cap_{i \geq 0} F^{-i}(V).$$

Note that $K(F)$ is connected if and only if all the critical points of F belongs to $K(F)$.

A real analytic extended map $F: I_F^n \rightarrow I_F^n$ has a polynomial-like extension if there is a polynomial-like extend map $\tilde{F}: U \rightarrow V$ such that $I \times \{i\} \subset U_i$ and $F = \tilde{F}$ on I_F^n .

2.3. Polynomial-like renormalization of real analytic extended maps. Let $U \subset \mathbb{C}_n$ be an open set. Given an analytic function $F: U \rightarrow \mathbb{C}_n$, define the open set

$$\mathcal{D}_U^n(F) := \bigcap_{i=0}^{n-1} F^{-i}U.$$

In other words, $\mathcal{D}_U^n(F)$ is the domain contained in \mathbb{C}_n where F^n is defined.

Let $F: U \rightarrow V$ be a complex-analytic extension of an extended map. Note that F does not need to be a polynomial-like extension. Suppose that the extended map F is r -times renormalizable, and let P_j and ℓ_j be the intervals and integers associated with the r th renormalization, as defined in Section 2.1. Define $n_k = \ell_{k+1} \bmod n - \ell_k$.

Suppose we can find a sequence i_k , $k = 1, \dots, n$, with $i_1 = 1$, simply connected domains \hat{U}_k and $\hat{V}_k \subset \mathbb{C} \times \{i_k\}$, such that

1. We have $\{i_k\}_k = \{1, 2, \dots, n\}$,
2. We have $P_k \subset \hat{U}_k$ and $\overline{\hat{U}_k} \subset \hat{V}_k$,
3. The domains \hat{U}_k and \hat{V}_k satisfies $\overline{\hat{U}_k} \subset \mathcal{D}_U^{n_k}(F)$, $F^{n_k}\hat{U}_k = \hat{V}_{k+1 \bmod n}$.
4. The map

$$F^{n_k}: \hat{U}_k \rightarrow \hat{V}_{k+1 \bmod n}$$

is a proper map for which $(0, i_k)$ is the unique critical point.

Let $A_j: \mathbb{C} \rightarrow \mathbb{C}$ be the affine maps defined in Section 2.1. Define $A: \mathbb{C}_n \rightarrow \mathbb{C}_n$ as $A(x, i) = (A_i(x), i)$. Then we can define

$$g_i: A(\hat{U}_j) \rightarrow A(\hat{V}_{j+1})$$

as $g_j = A \circ F^{n_k} \circ A^{-1}$. If

$$\hat{U} = \bigcup_i A(\hat{U}_i) \times \{i\}, \quad \hat{V} = \bigcup_i A(\hat{V}_i) \times \{i\},$$

then the map

$$R^r(F): \hat{U} \rightarrow \hat{V}$$

defined by $R^r(F)(x, i) = (g_i(x), i + 1)$ is a polynomial-like extension of the real renormalization $R^r(F)$ and it is called a polynomial-like r th renormalization of F . Note that \hat{U}_k and \hat{V}_k are not uniquely defined, however any polynomial-like extension of $R^r(F)$ does coincide on $I_{R^r(F)}^n$.

Lemma 2.1. *Let $x_1, \dots, x_n \in \mathbb{C}$, and $U_i \subset \mathbb{C}$ be open sets such that $x_i \in U_{i_k}$ and*

$$f_{i,k}: U_{i,k} \rightarrow \mathbb{C}, \quad k = 1, 2,$$

be holomorphic functions such that

- i. $f_{i,k}(x_i) = x_{i+1 \bmod n}$.
- ii. We have $|\lambda_1 \lambda_2 \cdots \lambda_n| > 1$, where $\lambda_i = f'_{i,1}(x_i) = f'_{i,2}(x_i)$.
- iii. Let

$$g_{i,k} = f_{(i+n-1) \bmod n, k} \circ \cdots \circ f_{(i+1) \bmod n, k} \circ f_{i,k}.$$

There is $q \geq 1$ such that $g_{i,1}^q = g_{i,2}^q$ for every i .

Then $f_{i,1}(x) = f_{i,2}(x)$ for every i and for every x close to x_i .

Proof. Due iii. we have that x_i is a repelling fixed point of $g_{i,k}$ and its multiplier is $\lambda_1 \lambda_2 \cdots \lambda_n$. By the Koenigs linearization theorem (see for instance Milnor [34, Theorem 8.2]) there is a *unique* germ of holomorphic function h_i at x_i such that $h'_i(x_i) = 1$ and

$$(3) \quad h_i \circ g_{i,1}(x) = g_{i,2} \circ h_i(x)$$

for x close to x_i . Note that the uniqueness of h_i and ii. implies

$$(4) \quad h_{i+1} \circ f_{i,1}(x) = f_{i,2} \circ h_i(x).$$

for x close to x_i . Note also that

$$(5) \quad h_i \circ g_{i,1}^q(x) = g_{i,2}^q \circ h_i(x)$$

But since $g_{i,1}^q = g_{i,2}^q$ this implies (due the uniqueness of the solution of the Schröder's equation in the Koenigs linearization theorem) that $h_i(x) = x$, so by (4) we have $f_{i,1} = f_{i,2}$ for every i . \square

Proposition 2.2 (Injectivity of Renormalization). *Let F_1, F_2 be real-analytic extended maps of type n with polynomial-like extensions of type n . Suppose that F_k , $k = 1, 2$ are renormalizable and $R(F_k)$, $k = 1, 2$, also have polynomial-like extensions of type n . Additionally assume that*

$$(6) \quad r \in \overline{\{F_k^\ell(s), \ell \geq 0\}}, \text{ every } r, s \in C(F_k), k = 1, 2,$$

Then $R(F_1) = R(F_2)$ implies $F_1 = F_2$.

Proof. We use an argument similar to de Melo and van Strien [13, Chapter VI, Proposition 1.1]. To simplify the notation we assume that $F_k(x, i) = F_k(-x, i)$. Let p_k be the period of the first renormalization of F_k and $q_k = p_k/n$. Using the notation of Section 2.1, we have $c_i = 0$, $a_i = 1$ and $b_i = 1$, for every $i \leq n$. Let $P_{1,k}$ be the interval of the first renormalization of F_k such that that $(0, 1) \in P_{1,k}$. Let $0 = \ell_{1,k} < \cdots < \ell_{n,k}$ be the iterations such that $(0, i_{j,k}) \in F_k^{\ell_{j,k}}(P_{1,k})$ for some $i_{j,k}$. Let $P_{j,k} = [-\beta_{j,k}, \beta_{j,k}]$ be the symmetrization of $F_k^{\ell_{j,k}}(P_{1,k})$, where $\beta_{j,k}$ is periodic. Let

$$Y_{j,k} = \left[-\frac{1}{\beta_{j,k}}, \frac{1}{\beta_{j,k}}\right].$$

The map

$$g_{j,k}: Y_{j,k} \rightarrow Y_{j,k}$$

defined by

$$g_{j,k}(x) = \frac{-1}{\beta_{j,k}} \pi_1(F_k^n(-\beta_{j,k}x, i_{j,k})).$$

is a multimodal map with a polynomial-like extension of degree 2^n and the real trace of its filled-in Julia set is $[-1/\beta_{j,k}, 1/\beta_{j,k}]$. Then $R(F_1) = R(F_2)$ implies that $g_{j,1}^{q_1} = g_{j,2}^{q_2}$ on $[-1, 1]$ and for every j . Moreover $g_{j,k}^{q_k}$ has a polynomial-like extension of degree 2^n whose real trace of its filled-in Julia set is $[-1, 1]$. Note that if $|\beta_{j,1}| < |\beta_{j,2}|$ then $Y_{j,2}$ is invariant by $g_{j,1}^{q_1}$, that implies that $Y_{j,2}$ would be a restricted interval of $g_{j,1}$, which is not possible since $g_{j,1}^{q_1}$ on $[-1, 1]$ is the first renormalization of $g_{j,1}$. So

$$(7) \quad \beta_{j,1} = \beta_{j,2} \text{ and } Y_{j,1} = Y_{j,2} \text{ for every } j$$

Counting the number of restricted intervals associated to $[-\beta_{j,k}, \beta_{j,k}]$ in $Y_{2,k}$ we obtain $p_1 = p_2$.

Note that $\ell_{1,k}$ is the number of critical values of $F_k^{\ell_{j,k}}$ in $[-1, 1] \times \{1\}$, which is equal to the number of critical values of $R(F_k)$ in $Y_{1,k} \times \{1\}$. Since $R(F_1) = R(F_2)$ and $Y_{1,2} = Y_{1,2}$ we conclude that $\ell_{1,1} = \ell_{1,2}$ and $i_{2,k} = 1 + \ell_{1,1}$ for $k = 1, 2$. Suppose by induction that $i_{j,1} = i_{j,2}$. Then $\ell_{j,k}$ is the number of critical values of $R(F_k)$ in $Y_{j,k} \times \{j\}$, so $\ell_{j,1} = \ell_{j,2}$ and consequently $i_{j+1,k} = i_{j+1,1} + \ell_{j,1}$. So

$$(8) \quad i_{j,1} = i_{j,2} \text{ and } \ell_{j,1} = \ell_{j,2} \text{ for every } j.$$

Finally due (7), (8) and $R(F_1) = R(F_2)$ we have that

$$(9) \quad F_1^{\ell_{j+1,1} - \ell_{j,1}} = F_2^{\ell_{j+1,2} - \ell_{j,2}}$$

in a neighborhood of the point $(-1, i_{j,1})$ and $F_1^{\ell_{j+1,1} - \ell_{j,1}}(-1, i_{j,1}) = (-1, i_{j+1,1})$ for every j .

Let $\lambda_{i,k} = DF_k(-1, i) > 0$. We claim that $\lambda_{i,1} = \lambda_{i,2}$ for every i . Indeed, let $p = p_1 = p_2$, $q = q_1 = q_2$ and $\ell_i = \ell_{i,1} = \ell_{i,2}$. So $g_{j,1}^q = g_{j,2}^q$ and (7) implies that $F_1^{qn} = F_2^{qn}$ in a neighborhood of $[-1, 1] \times \{1, \dots, n\}$. In particular

$$(\lambda_{1,1} \cdots \lambda_{n,1})^q = (\lambda_{1,2} \cdots \lambda_{n,2})^q,$$

so

$$(10) \quad \lambda_{1,1} \cdots \lambda_{n,1} = \lambda_{1,2} \cdots \lambda_{n,2}.$$

There is exactly one $j \leq n$ such that $(0, 1) \in F_1^{\ell_j}(P_{1,1})$, that is the unique i_1 satisfying $\ell_{i_1} = w_1 n + 1$, for some $w_1 \in \mathbb{N}$. In particular

$$DF_k^{\ell_{i_1}}(-1, 0) = (\lambda_{1,k} \cdots \lambda_{n,k})^{w_1} \lambda_{1,k}.$$

Due (9) we have $DF_1^{\ell_{i_1}}(-1, 0) = DF_2^{\ell_{i_1}}(-1, 0)$, so it follows from (10) that $\lambda_{1,1} = \lambda_{1,2}$. Suppose by induction that $\lambda_{j,1} = \lambda_{j,2}$ for $j < j_0 < n$. Then there is a unique $\ell_{i_{j_0}}$ such that $\ell_{i_{j_0}} = w_{j_0} n + j_0$ for some $w_{j_0} \in \mathbb{N}$ and consequently

$$DF_k^{\ell_{i_{j_0}}}(-1, 0) = (\lambda_{1,k} \cdots \lambda_{n,k})^{w_{j_0}} \lambda_{1,k} \lambda_{2,k} \cdots \lambda_{j_0-1,k} \lambda_{j_0,k}.$$

It follows from the induction assumption, $DF_1^{\ell_{i_{j_0}}}(-1, 0) = DF_2^{\ell_{i_{j_0}}}(-1, 0)$ and (10) that $\lambda_{j_0,1} = \lambda_{j_0,2}$. So $\lambda_{j,1} = \lambda_{j,2}$ for every $j \leq n - q$. We conclude that $\lambda_{n,1} = \lambda_{n,2}$ due (10). This concludes the proof of the claim.

Define $f_{i,k}(x) = \pi_1(F_k(x, i))$ and $x_i = -1$. By Lemma 2.1 we have that $f_{i,1}(x) = f_{i,2}(x)$ for every i and x close to -1 , so $F_1 = F_2$. \square

2.4. Complex bounds and rigidity of real analytic, infinitely renormalizable extended maps with bounded combinatorics. Here we summarize results in [40].

Theorem 1. *Let $\sigma = (\sigma_i)_{i \in \mathbb{Z}} \in \mathcal{C}_{p,n}^{\mathbb{Z}}$. Then there exists a unique sequence of real analytic maps $F_{\sigma,i}$, $i \in \mathbb{Z}$, satisfying the following conditions*

1. *The map $F_{\sigma,i}$ is renormalizable and $R(F_{\sigma,i}) = F_{\sigma,i+1}$.*
2. *The first renormalization of $F_{\sigma,i}$ has combinatorics σ_i .*
3. *There exist polynomial-like extensions $F_{\sigma,i}: U_{\sigma}^i \rightarrow V_{\sigma}^i$, where*

$$\inf_i \quad \text{mod}(V_{\sigma}^i \setminus U_{\sigma}^i) > 0.$$

If $U \subset \mathbb{C}$ is a bounded open set such that $0 \in U$, denote by $\mathcal{B}(U)$ the Banach space of all holomorphic functions $g: U \rightarrow \mathbb{C}$ that has a continuous extension to \overline{U} and a critical point at 0, with the sup norm. If $-1 \in \overline{U}$ let $\mathcal{B}_{nor}(U)$ be the affine subspace of maps $g \in \mathcal{B}(U)$ such that $g(-1) = -1$.

In an analogous way, let $U \subset \mathbb{C}_n$ be a bounded open set such that

$$U_i = (\mathbb{C} \times \{i\}) \cap U \neq \emptyset$$

and $(0, i) \in U$, for every i and consider the set $\mathcal{B}(U)$ of all holomorphic functions $G: U \rightarrow \mathbb{C}_n$ with the following properties:

1. G has a continuous extension to \overline{U} .
2. G has critical points at $(0, i)$, for every i .
3. $G(U_i) \subset \mathbb{C} \times \{i + 1 \bmod n\}$.

Theorem 2. (Complex Bounds [39][40]) *There exists $\epsilon_0 > 0$ with the following property. If F is a real analytic extended map that is infinitely renormalizable with combinatorics in $\mathcal{C}_{p,n}^{\mathbb{N}}$ and with a complex analytic (but not necessarily polynomial-like) extension $F \in \mathcal{B}(U)$ then there exist a neighbourhood $V_F \subset \mathcal{B}(U)$ of F and k_0 with the following property. For every $k \geq k_0$ and every real analytic and infinitely renormalizable $G \in V_F$ with combinatorics in $\mathcal{C}_{p,n}^{\mathbb{N}}$ the map G has a polynomial-like k th renormalization*

$$R^k(G): U^k \rightarrow V^k$$

such that

$$\text{mod}(V^k \setminus U^k) > \epsilon_0.$$

If $(-1, i) \in \overline{U}$ for every i , we can also consider the subset $\mathcal{B}_{nor}(U)$ of all maps $G \in \mathcal{B}(U)$ such that $G(-1, i) = (-1, i + 1 \bmod n)$ for every i .

Denote $\pi(x, i) = x$. We identify $\mathcal{B}(U)$ with the Banach space

$$(11) \quad \mathcal{B}(\pi(U_1)) \times \mathcal{B}(\pi(U_2)) \times \cdots \times \mathcal{B}(\pi(U_n))$$

in the following way. For each $G \in \mathcal{B}(U)$ there is a unique decomposition

$$(12) \quad (g_1, \dots, g_n) \in \mathcal{B}(\pi(U_1)) \times \mathcal{B}(\pi(U_2)) \times \cdots \times \mathcal{B}(\pi(U_n)),$$

where g_i is defined by $g_i(x) = \pi \circ G(x, i)$ and for each n -uple as in (12) we can associate $G \in \mathcal{B}(U)$ defined by $G(x, i) = (g_i(x), i + 1 \bmod n)$. With this identification $\mathcal{B}_{nor}(U)$ turns out to be an affine subspace of $\mathcal{B}(U)$. So given $F \in \mathcal{B}_{nor}(U)$ we can consider the tangent space of $\mathcal{B}_{nor}(U)$ at F , denoted by $T_F \mathcal{B}_{nor}(U)$. using the identification (11) then $T_F \mathcal{B}_{nor}(U)$ is the subspace of

$$(v_1, \dots, v_n) \in \mathcal{B}(\pi(U_1)) \times \mathcal{B}(\pi(U_2)) \times \cdots \times \mathcal{B}(\pi(U_n))$$

such that $v_i(-1) = 0$ for $i = 1, \dots, n$. In particular $T_F \mathcal{B}_{nor}(U)$ does not depend on F , so sometimes we will write $T \mathcal{B}_{nor}(U)$.

Given $\delta > 0$ and $\theta > 0$, let $D_{\delta, \theta}$ be the set

$$\{x \in \mathbb{C} : \text{dist}(x, [-1, 1]) < \delta \text{ and } |\text{Im}(x)| < \theta(\text{Re}(x) + 1)\} \times \{1, \dots, n\}$$

Define

$$\Omega_{p,n} = \{F_{\sigma, 0}\}_{\sigma \in \mathcal{C}_{p,n}^{\mathbb{Z}}}$$

Indeed, due Theorem 1 we have that

$$\Omega_{p,n} = \{F_{\sigma, i}\}_{\sigma \in \mathcal{C}_{p,n}^{\mathbb{Z}}}$$

for every i . Using Theorem 2 and Theorem 1 one can show that there exists ϵ_0 such that for every $F_{\sigma,0} \in \Omega_{p,n}$ there exists a polynomial-like extension $F_{\sigma,0} : U_\sigma^0 \rightarrow V_\sigma^0$ such that $\text{mod}(V_\sigma^0 \setminus U_\sigma^0) > \epsilon_0$. There exists δ_0 such that for every simply connected domains $Q \supset W \supset [-1, 1]$ such that $\text{mod}(Q \setminus W) \geq \epsilon_0/2$ we have

$$(13) \quad \{x \in \mathbb{C} : \text{dist}(x, [-1, 1]) \leq \delta_0\} \subset Q.$$

In particular

$$\overline{D_{\delta_0, \theta}} \subset U_\sigma^0$$

for every $\theta > 0$ and for every $\sigma \in \mathcal{C}_{p,n}$. In particular $\Omega_{p,n} \subset \mathcal{B}_{\text{nor}}(D_{\delta_0, \theta})$.

Consider the shift operator on $\mathcal{C}_{p,n}^{\mathbb{Z}}$, that is, if $\sigma = (\sigma_i)_{i \in \mathbb{Z}}$ then $S(\sigma) = \sigma'$, where $\sigma'_i = \sigma_{i+1}$.

Corollary 2.3. *The set $\Omega_{p,n} \subset \mathcal{B}_{\text{nor}}(D_{\delta_0, \theta})$ is a Cantor set. Indeed the map $H : \mathcal{C}_{p,n}^{\mathbb{Z}} \rightarrow \Omega_{p,n}$ given by*

$$H(\sigma) = F_{\sigma,0},$$

is a homeomorphism. Moreover $R(F_{\sigma,0}) = F_{S(\sigma),0}$.

Proof. The map H is continuous and onto due [40, Section 7.1]. The injectivity of H follows from Proposition 2.2. \square

3. COMPLEXIFICATION OF THE RENORMALIZATION OPERATOR \mathcal{R} .

Given $\theta_0 > 0$, by Theorem 2 for each $F \in \Omega_{p,n}$ there exist a neighbourhood $V_F \subset \mathcal{B}_{\text{nor}}(D_{\delta_0, \theta_0})$ of F and k_F such that for every real map $G \in V_F$ that is infinitely renormalizable with combinatorics in $\mathcal{C}_{p,n}$ and for every $k \geq k_F$ we have a polynomial-like k th renormalization $R^k(G) : \hat{U} \rightarrow \hat{V}$ with $\text{mod}(\hat{V} \setminus \hat{U}) > \epsilon_0$. In particular $R^k(G) \in \mathcal{B}_{\text{nor}}(D_{\delta_0, \theta_0})$. Since $\Omega_{p,n}$ is a compact set, choose a finite subcover $\{V_{F_i}\}_{i \leq \ell}$ of $\Omega_{p,n}$. Let $k_0 = \max_{i \leq \ell} k_{F_i}$ and $\mathcal{V} = \cup_{i \leq \ell} V_{F_i}$.

Let H be the homeomorphism defined in Corollary 2.3. For every $\gamma = (\gamma_1, \dots, \gamma_{k_0}) \in \mathcal{C}_{p,n}^{k_0}$ define the compact set

$$\Omega_{p,n}(\gamma) = H(\{\sigma \in \mathcal{C}_{p,n}^{\mathbb{Z}} : \sigma_i = \gamma_i \text{ for } 1 \leq i \leq k_0\}).$$

We have

$$d_1 = \inf\{\text{dist}_{\mathcal{B}_{\text{nor}}(D_{\delta_0, \theta_0})}(G_1, G_2) : G_1 \in \Omega_{p,n}(\hat{\gamma}), G_2 \in \Omega_{p,n}(\tilde{\gamma}), \hat{\gamma} \neq \tilde{\gamma}\} > 0.$$

Given $F \in \Omega_{p,n}$, consider the intervals $P_{F,j}$, $j = 1, \dots, n$, integers n_j , corresponding the restrictive intervals of the k_0 th renormalization of F , as in Section 2.3. Each interval $P_{F,j}$ contains a unique repelling periodic point $(\beta_{F,j}, i_j)$ in its boundary. These repelling periodic points have a complex analytic continuation $(\beta_{G,j}, i_j)$ for every G in a connected neighbourhood \tilde{W}_F of F in $\mathcal{B}_{\text{nor}}(D_{\delta_0, \theta_0})$ that is also a repelling periodic point for G . Note that for a real map G the point $\beta_{G,j}$ is real and we can assume that it has the same combinatorics as $\beta_{F,j}$. We can also assume that $\tilde{W}_F \subset \mathcal{V}$ and that the diameter of \tilde{W}_F is smaller than $d_1/2$.

Let $d_2 < d_1$ be a Lebesgue number of the cover $\{\tilde{W}_F\}_{F \in \Omega_{p,n}}$ of $\Omega_{p,n}$. For every $F \in \Omega_{p,n}$ choose a connected neighbourhood $W_F \subset \tilde{W}_F$ of F so that

$$\text{diam}_{\mathcal{B}_{\text{nor}}(D_{\delta_0, \theta_0})} W_F < d_2/4.$$

Let $F_1, F_2 \in \Omega_{p,n}$ and consider the complex analytic continuations $(\beta_{G,j}^1, i_j^1)$, $(\beta_{G,j}^2, i_j^2)$ of $(\beta_{F_1,j}, i_j^1)$ and $(\beta_{F_2,j}, i_j^2)$ defined for every $G \in W_{F_1}$ and $G \in W_{F_2}$

respectively. Suppose that $W_{F_1} \cap W_{F_2} \neq \emptyset$. We claim that $i_j^1 = i_j^2$ and $\beta_{G,j}^1 = \beta_{G,j}^2$ for every $G \in W_{F_1} \cap W_{F_2}$ and j . Since the diameter of $W_{F_1} \cup W_{F_2}$ is smaller than d_2 we have that $W_{F_1} \cup W_{F_2} \subset \tilde{W}_{F_3}$, for some $F_3 \in \Omega_{p,n}$. Note that the distance between two maps in $\{F_1, F_2, F_3\}$ is smaller than d_1 . In particular the combinatorics of their k_0 th renormalizations are the same, so $i_j^1 = i_j^2 = i_j^3$ for every j . Consider the complex analytic continuation $(\beta_{G,j}^3, i_j)$ of $(\beta_{F_3,j}, i_j)$ defined for $G \in \tilde{W}_{F_3}$. Then $(\beta_{F_1,j}^3, i_j)$ and $(\beta_{F_2,j}, i_j)$ are repelling periodic points with the same combinatorics. Since F_1 has negative schwarzian derivative, the minimal principle implies that $\beta_{F_1,j}^3 = \beta_{F_1,j}$. In an analogous way $\beta_{F_2,j}^3 = \beta_{F_2,j}$. The uniqueness of the analytic continuation of a repelling periodic point implies that $\beta_{G,j}^3 = \beta_{G,j}^1$ for $G \in W_{F_1}$ and $\beta_{G,j}^3 = \beta_{G,j}^2$ for $G \in W_{F_2}$. This concludes the proof of the claim.

In particular the function

$$G \mapsto (\beta_{G,j}, i_j)$$

is well defined and complex analytic in $\mathcal{W} = \cup_{F \in \Omega_{p,n}} W_F$. There is a small abuse of notation here since i_j depends on G , but it is a locally constant function.

Fix $G \in W_F$. Let $A_{G,j}: \mathbb{C} \times \{i_j\} \rightarrow \mathbb{C} \times \{j\}$ be the affine transformation that maps $(\beta_{G,j}, i_j)$ to $(-1, j)$ and $(0, i_j)$ to $(0, j)$, and $A_G: \mathbb{C}_n \rightarrow \mathbb{C}_n$ as $A_G(x, i) = (A_{G,i}(x), i)$. Let $D^{F,j}$ be the set

$$\overline{A_{F,j}^{-1}(\{z \in \mathbb{C} : \text{dist}(z, [-1, 1]) < \delta_0 \text{ and } |\text{Im}(z)| < \theta_0(\text{Re}(z) + 1)\} \times \{j\})}.$$

Since $\text{mod}(\hat{V} \setminus \hat{U}) > \epsilon_0$ we have that

$$D^{F,j} \subset \hat{U}_j \subset \mathcal{D}_{D_{\delta_0, \theta_0}}^{n_j}(F),$$

Moreover, due the complex bounds, reducing θ_0 and δ_0 we can assume that the interior of the sets in the family

$$\{F^m(D^{F,j})\}_{m < n_j}$$

are pairwise disjoint, and the intersection of the closure of every two of those sets is contained in

$$\{F^m(\beta_{F,j}, i_j)\}_{m < n_j}.$$

Let $G \in W_F$ and define the set $D^{G,j}$ as

$$\overline{A_{G,j}^{-1}(\{z \in \mathbb{C} : \text{dist}(z, [-1, 1]) < \delta_0 \text{ and } |\text{Im}(z)| < \theta_0(\text{Re}(z) + 1)\} \times \{j\})}.$$

Reducing the neighbourhood W_F of F and θ_0 we can assume that

$$D^{G,j} \subset \mathcal{D}_{D_{\delta_0, \theta_0}}^{n_j}(G),$$

for every $G \in W_F$ and furthermore the interior of the sets in the family

$$\{G^m(D^{G,j})\}_{m < n_j}$$

are pairwise disjoint, and the intersection of the closure of every two of those sets is contained in

$$\{G^m(\beta_{G,j}, i_j)\}_{m < n_j}.$$

Define the complexification of the renormalization operator

$$\mathcal{R}: \mathcal{W} \rightarrow \mathcal{B}_{nor}(D_{\delta_0, \theta_0})$$

as

$$(14) \quad \mathcal{R}(G)(x, j) = A_{G,j+1} \circ G^{n_j} \circ A_{G,j}^{-1}(x, j)$$

if $G \in W_F$. The operator \mathcal{R} is a compact complex analytic map. From now on denote $U = D_{\delta_0, \theta_0}$.

Remark 3.1. Let \tilde{U} be a little larger complex open domain that contains \overline{U} . Consider the complex analytic transformation

$$\tilde{\mathcal{R}}: \mathcal{W} \rightarrow \mathcal{B}_{nor}(\tilde{U}).$$

defined exactly as in (14). Let

$$i: \mathcal{B}_{nor}(\tilde{U}) \rightarrow \mathcal{B}_{nor}(U)$$

be the compact linear inclusion between these spaces. Then $\mathcal{R} = i \circ \tilde{\mathcal{R}}$, so the complexification of the renormalization operator is a strongly compact operator as defined in [43].

Let $v \in T_G \mathcal{B}_{nor}(U)$. If $z \in U$ and $G^j(z) \in U$ for every $j < i$ then $(G + tv)^i$ is defined in a neighbourhood of z and we can define

$$(15) \quad a_i(z) = \frac{\partial}{\partial t}(G + tv)^i|_{t=0}(z) = \sum_{j=0}^{i-1} DG^{i-j-1}(G^{j+1}(z))v(G^j(z)).$$

Given $F \in \Omega_{p,n}$ and $G \in W_F$. For each $v \in T_G \mathcal{B}_{nor}(U)$ and $z \in U_j$ we have

$$\begin{aligned} (D\mathcal{R}_G \cdot v)(x, j) &= \frac{\partial}{\partial t} A_{G+tv, j+1} \circ (G + tv)^{n_j} \circ A_{G+tv, j}^{-1}(x, j)|_{t=0} \\ &= -\frac{\partial_G \beta_{G, j+1} \cdot v}{\beta_{G, j+1}} \cdot A_{G, j+1} \circ G^{n_j} \circ A_{G, j}^{-1}(x, j) \\ &\quad - \frac{1}{\beta_{G, j+1}} (a_{n_j} \circ A_{G, j}^{-1}(x, j) + (\partial_x G^{n_j}) \circ A_{G, j}^{-1}(x, j) \cdot (-\partial_G \beta_{G, j} \cdot v \ x, j)). \end{aligned}$$

Theorem 3. Let $F \in \mathcal{W}$. Then $D_F \mathcal{R}(T_F \mathcal{B}_{nor}(U))$ is dense in $T_{\mathcal{R}F} \mathcal{B}_{nor}(U)$.

Proof. The proof is quite similar to the proof of the analogous statement in [3]. Let $w \in T_{\mathcal{R}F} \mathcal{B}_{nor}(U)$. Then $w(-1, k) = 0$ and $w'(0, k) = 0$ for every k . We are going to define a function

$$\hat{v}: \cup_j \cup_{m < n_j} G^m(D^{G, j}) \rightarrow \mathbb{C}$$

in the following way. Define the function \hat{v} as 0 on

$$\cup_j \cup_{0 < m < n_j} G^m(D^{G, j}),$$

and

$$\hat{v}(z) = [DG^{n_j-1}(G(z))]^{-1} \cdot w \circ A_{G, j}(z)$$

for $z \in D^{G, j}$. Also define $\hat{v}(-1, k) = 0$ for every k . Then \hat{v} is well defined, it is continuous on

$$\Lambda = \cup_j \cup_{m < n_j} G^m(D^{G, j}) \cup \{(-1, k)\}_k,$$

and it is complex analytic in the interior of Λ .

Moreover \hat{v} vanishes on the orbit of the periodic points $\{\beta_{G, j}\}_j$. Since $\mathbb{C} \times \{i\} \setminus \Lambda$ is a connected set, by Mergelyan's Theorem for each given $\epsilon > 0$ and i we can find a polynomial q_i such that $|\hat{v}(z) - q_i(z)| < \epsilon$ for $z \in \Lambda_i = \Lambda \cap \mathbb{C} \times \{i\}$. Define

$$\hat{q}_i(z) = q_i(z) - q'_i(0, i)z - q_i(-1, i) - q'_i(0, i)$$

Note that $\hat{q}'_i(0, i) = 0$ and $\hat{q}_i(-1, i) = 0$. Define $q(x, i) = \hat{q}_i(x)$. We have that $q \in T_G \mathcal{B}_{nor}(U)$ and

$$|D_G \mathcal{R} \cdot q - w|_{\mathcal{B}(U)} \rightarrow_{\epsilon \rightarrow 0} 0.$$

□

4. ACTION OF $D\mathcal{R}$ ON HORIZONTAL DIRECTIONS.

4.1. Horizontal direction. Let $F: I_F^n \rightarrow I_F^n$ be a real analytic extended map that is either infinitely renormalizable with bounded combinatorics in $\mathcal{C}_{p,n}$ or whose critical points belongs to the same periodic orbit. A continuous function

$$v: I_F^n \rightarrow T\mathbb{C}_n$$

is a *horizontal direction* of F if

1. For each $x \in I_F^n$ we have $v(x) \in T_{F(x)}\mathbb{C}_n$.
2. The function v is real analytic in the interior of I_F^n .
3. There is a quasiconformal vector field

$$\alpha: W \rightarrow T\mathbb{C}_n,$$

defined in a complex neighbourhood W of the post critical set of F , such that

$$(16) \quad v(x) = \alpha(F(x)) - DF(x) \cdot \alpha(x)$$

for every x in the post critical set.

4. We have $\alpha(c) = 0$ for every critical point c of F .

Denote by E_F^h the set of $v \in T_F\mathcal{B}_{nor}(U)$ such that v is horizontal. Of course E_F^h is a linear subspace of $T_F\mathcal{B}_{nor}(U)$.

Proposition 4.1 (Infinitesimal pullback argument. Avila, Lyubich and de Melo [3]). *Let $F \in \Omega_{n,p}$. Let*

$$F: W \rightarrow V$$

be a polynomial-like extension of F and $v \in \mathcal{B}(W) \cap T_F\mathcal{B}_{nor}(U)$ such that there exists a quasiconformal vector field α , defined in a neighbourhood of the post critical set of F , such that

$$(17) \quad v(x) = \alpha \circ F(x) - DF(x) \cdot \alpha(x)$$

for every $x \in P(F)$. In particular $v \in E_F^h$. Reducing a little bit the domain W , there exists a quasiconformal vector field extension $\alpha: W \rightarrow \mathbb{C}$ such that (17) holds for every $x \in W$.

Proposition 4.2 (Invariance). *Let $F \in \Omega_{n,p}$. Then*

$$(18) \quad D_F\mathcal{R}(E_F^h) \subset E_{\mathcal{R}F}^h,$$

$$(19) \quad (D_F\mathcal{R})^{-1}(E_{\mathcal{R}F}^h) \subset E_F^h.$$

Proof. The proof of (18) is quite similar to the proof of a similar statement in [41]. Indeed, consider a_i as in (15). Note that

$$a_i(z) = v(F^{i-1}) + DF(F^{i-1}(z))a_{i-1}(z).$$

By an inductive argument one can show that

$$a_i = \alpha \circ F^i - DF^i \cdot \alpha$$

on $P(F)$. Denote

$$\alpha(\beta_{F,j+1}) = \partial_F \beta_{F,j+1} \cdot v$$

then if $z = (x, j) \in P(F)$ we have

$$\begin{aligned}
& (D\mathcal{R}_F \cdot v)(x, j) \\
&= -\frac{\partial_F \beta_{F,j+1} \cdot v}{\beta_{F,j+1}} \cdot A_{F,j+1} \circ F^{n_j} \circ A_{F,j}^{-1}(x, j) \\
&\quad - \frac{1}{\beta_{F,j+1}} (a_{n_j} \circ A_{F,j}^{-1}(x, j) + (DF^{n_j}) \circ A_{F,j}^{-1}(x, j) \cdot (-\partial_F \beta_{F,j} \cdot v \ x, j)) \\
&= -\frac{\alpha(\beta_{F,j+1})}{\beta_{F,j+1}} \cdot (\mathcal{R}F)(z) \\
&\quad - \frac{1}{\beta_{F,j+1}} \alpha \circ A_{F,j+1}^{-1} \circ A_{F,j+1} \circ F^{n_j} \circ A_{F,j}^{-1}(x, j) + \frac{\beta_{F,j}}{\beta_{F,j+1}} DF^{n_j} \circ A_{F,j}^{-1}(x, j) \cdot \frac{1}{\beta_{F,j}} \alpha \circ A_{F,j}^{-1}(x, j) \\
&\quad + D_z(\mathcal{R}F) \cdot \left(\frac{\alpha(\beta_{F,j})}{\beta_{F,j}} \ x, j \right) \\
&= -\frac{\alpha(\beta_{F,j+1})}{\beta_{F,j+1}} \cdot (\mathcal{R}F)(z) \\
&\quad - \frac{1}{\beta_{F,j+1}} \alpha \circ A_{F,j+1}^{-1} \circ (\mathcal{R}F)(z) + D_z(\mathcal{R}F) \cdot \frac{1}{\beta_{F,j}} \alpha \circ A_{F,j}^{-1}(x, j) \\
&\quad + D_z(\mathcal{R}F) \cdot \left(\frac{\alpha(\beta_{F,j})}{\beta_{F,j}} \ x, j \right).
\end{aligned}$$

Define the vector field $r(\alpha)$ as

$$(20) \quad r(\alpha)(x, j) = -\frac{1}{\beta_{F,j}} \alpha \circ A_{F,j}^{-1}(x, j) - \left(\frac{\alpha(\beta_{F,j})}{\beta_{F,j}} \cdot x, j \right)$$

for $z = (x, j) \in U_j$. Then

$$(21) \quad (D\mathcal{R}_F \cdot v)(z) = r(\alpha) \circ (\mathcal{R}F)(z) - D_z(\mathcal{R}F) \cdot r(\alpha)(z)$$

for z in the postcritical set of $\mathcal{R}F$. Note that $r(\alpha)$ is a quasiconformal vector field in a neighbourhood of the post critical set of $\mathcal{R}F$. So $D\mathcal{R}_F \cdot v \in E_{\mathcal{R}F}^h$.

Now suppose that $v \in (D_F \mathcal{R})^{-1}(E_{\mathcal{R}F}^h)$. Then $D\mathcal{R}_F \cdot v \in E_{\mathcal{R}F}^h$, so there exists a quasiconformal vector field $\gamma: \mathbb{C}_n \rightarrow \mathbb{C}$ such that

$$(22) \quad (D\mathcal{R}_F \cdot v)(z) = \gamma \circ (\mathcal{R}F)(z) - D_z(\mathcal{R}F) \cdot \gamma(z).$$

for every z in a neighbourhood of the post critical set of $\mathcal{R}F$. Define

$$\delta_j = \partial_t \beta_{F+tv,j} \big|_{t=0} = \partial_F \beta_{F,j} \cdot v$$

Define α in $A_{F,j}(U)$ as

$$\alpha(z) = \beta_{F,j} \gamma \circ A_{F,j}^{-1}(z) + \delta_j A_{F,j}^{-1}(z).$$

Let z be a point very close to the post critical set of F . Then

$$\{k \geq 0 \text{ s.t. } F^k(z) \in \cup_{j \leq n} A_{F,j}(U)\} \neq \emptyset$$

Let $k(z)$ be a minimal element of the above set. Note that $z \mapsto k(z)$ is locally constant. We define $\alpha(z)$ for z close to the post critical set of F by induction of $k(z)$. We already defined $\alpha(z)$ when $k(z) = 0$. If $k(z) > 0$ then $k(F(z)) = k(z) - 1$ and we define

$$\alpha(z) = \frac{v(z) + \alpha(F(z))}{DF(z)}.$$

One can check that α is a quasiconformal vector field and

$$v = \alpha(F(z)) - DF(z)\alpha(z)$$

in a neighbourhood of the post critical set of F , so $v \in E_F^h$. \square

Proposition 4.3. *Let $F \in \Omega_{n,p}$. Then $D\mathcal{R}_F$ is injective.*

Proof. Let v be such that $D\mathcal{R}_F \cdot v = 0$. By Proposition 4.2 we have that $v \in E_F^h$. By Proposition 4.1 there is a quasiconformal vector field α , defined in a neighborhood of the Julia set of F , satisfying (17) for every x on its Julia set. Let $r(\alpha)$ be the quasiconformal vector field defined by (20). Then by (21) we have that $r(\alpha)$ satisfies

$$0 = r(\alpha) \circ (\mathcal{R}F)(z) - D_z(\mathcal{R}F) \cdot r(\alpha)(z).$$

for every z in the Julia set of $\mathcal{R}F$. We can easily conclude that $r(\alpha)(z) = 0$ at every repelling periodic point z of $\mathcal{R}F$ and consequently at every point of its Julia set. By (20) we have that α is zero at every point of the small Julia sets of F corresponding to this renormalization and, by (17) we have that v vanishes in these small Julia sets as well. So $v = 0$ everywhere. \square

Proposition 4.4 (Closedness). *Let $F_k \in \Omega_{n,p}$ and $v_k \in E_{F_k}^h \subset T\mathcal{B}_{nor}(U)$ be sequences such that (F_k, v_k) converges to $(F, v) \in \mathcal{B}_{nor}(U) \times T\mathcal{B}_{nor}(U)$. Then $F \in \Omega_{p,n}$ and $v \in E_F^h$. In particular E_F^h is Banach subspace of $T_F\mathcal{B}_{nor}(U)$.*

Proof. Due the definition of the operator \mathcal{R} , the map $\mathcal{R}F$ has a polynomial-like extension

$$\mathcal{R}F: W \rightarrow V,$$

with $\overline{U} \subset W$. Reducing V a little bit, we can assume ∂V is a finite union of analytic curves and that for k large enough the map

$$\mathcal{R}F_k: W_k \rightarrow V,$$

where $W_k \subset \mathbb{C}_n$, $\overline{U} \subset W_k$, is the set whose connected components are the connected components of

$$(\mathcal{R}F_k)^{-1}V$$

that intersect $\{(0, j)\}_j$, is a polynomial-like extension of $\mathcal{R}F_k$. Since $v_k \in E_{F_k}^h$ we have that $D_{F_k}\mathcal{R} \cdot v_k \in E_{\mathcal{R}F_k}^h$, so there exists a quasiconformal vector field $\tilde{\gamma}^k$ such that

$$(D\mathcal{R}_{F_k} \cdot v_k)(z) = \tilde{\gamma}^k \circ (\mathcal{R}F_k)(z) - D_z(\mathcal{R}F_k) \cdot \tilde{\gamma}^k(z).$$

holds for z in a neighbourhood of the post critical set of $\mathcal{R}F_k$.

Now we use the infinitesimal pullback argument in Avila, Lyubich and de Melo [3]. For each k , there exist $C > 0$ and a quasiconformal vector field $\gamma_0^k: \mathbb{C}_n \rightarrow \mathbb{C}$ with the following properties

1. The vector field γ_0^k vanishes outside V . Moreover $\gamma_0^k(-1) = \gamma_0^k(0) = 0$.
2. It satisfies

$$(D\mathcal{R}_{F_k} \cdot v_k)(z) = \gamma_0^k \circ (\mathcal{R}F_k)(z) - D_z(\mathcal{R}F_k) \cdot \gamma_0^k(z).$$

for every $z \in \partial W_k$.

3. The vector field γ_0^k is C^∞ in a neighbourhood of

$$\overline{V \setminus W_k}$$

and

$$|\overline{\partial}\gamma_0^k| \leq C$$

on this set.

4. We have $\gamma_0^k = \tilde{\gamma}^k$ in a neighbourhood of the post critical set of $\mathcal{R}F_k$.

Define by induction γ_j^k as 0 outside V and

$$\gamma_{j+1}^k(z) = \frac{\gamma_j^k \circ (\mathcal{R}F_k)(z) - (D\mathcal{R}_{F_k} \cdot v_k)(z)}{D_z(\mathcal{R}F_k)}$$

on $V \setminus \{(0, m)\}_m$, and $\gamma_{j+1}^k(0, m) = 0$.

Using the McMullen compactness criterion for quasiconformal vectors fields [32, Corollary A.11], one can prove that for each k the sequence

$$\hat{\gamma}_j^k = \frac{1}{j} \sum_{t=0}^{j-1} \gamma_t^k$$

has a convergent subsequence, uniform on compact subsets of \mathbb{C}_n . Moreover such limits are quasiconformal vectors fields. Let γ_∞^k be one of these limits. Since the filled-in Julia sets of the polynomial-like extensions of $\mathcal{R}F_k$ do not support invariant line fields [40] we conclude that $|\bar{\partial}\gamma_\infty^k| \leq C$ on \mathbb{C}_n . Note that

$$(23) \quad (D\mathcal{R}_{F_k} \cdot v_k)(z) = \gamma_\infty^k \circ (\mathcal{R}F_k)(z) - D_z(\mathcal{R}F_k) \cdot \gamma_\infty^k(z), \quad z \in \bar{U}.$$

By the compactness criterion for quasiconformal vectors fields in McMullen [32] we can consider a convergent subsequence $\gamma^{k_t} \rightarrow_t \gamma$, where γ is a quasiconformal vector field on \mathbb{C}_n and the convergence is uniform on compact subsets of \mathbb{C}_n . By (23) we have

$$(24) \quad (D\mathcal{R}_F \cdot v)(z) = \gamma \circ (\mathcal{R}F)(z) - D_z(\mathcal{R}F) \cdot \gamma(z), \quad z \in \bar{U},$$

so $D\mathcal{R}_F \cdot v \in E_{\mathcal{R}F}^h$, so by (19) we have $v \in E_F^h$. \square

Proposition 4.5 (Contraction on the horizontal directions). *There exist K and $\theta_1 > 1$ such that for every $F \in \Omega_{n,p}$ and $v \in E_F^h$ we have*

$$|D_F \mathcal{R}^i \cdot v|_{T\mathcal{B}_{nor}(U)} \leq K \theta_1^{-i} |v|_{T\mathcal{B}_{nor}(U)}.$$

We do not provide a proof for Proposition 4.5 since it can be proven in exactly the same way it is done in the unimodal setting. One can use the argument by Lyubich [27, Theorem 6.3] using the Schwarz's lemma and the rigidity of McMullen's towers [32]. An infinitesimal argument using the rigidity of McMullen's towers and the compactness of the renormalization operator is given in [41, Proposition 3.9] (in the case of the fixed point of the period doubling renormalization) can be also applied here. We also cite the new methods by Avila and Lyubich [2] to prove the contraction in the horizontal directions in the case of unimodal unbounded combinatorics.

Proposition 4.6 (Contraction on the hybrid classes). *There exists $\lambda_1 \in (0, 1)$ with the following property. Let F be a real-analytic polynomial-like map of type n that is infinitely renormalizable with combinatorics bounded by p . Then there exist $G \in \Omega_{n,p}$ and $k_0 = k_0(F)$ and $C = C(F)$ such that $\mathcal{R}^k F \in \mathcal{B}(U)$ for every $k \geq k_0$ and*

$$|\mathcal{R}^k F - \mathcal{R}^k G|_{\mathcal{B}_{nor}(U)} \leq C \lambda_1^k \text{ for } k \geq k_0.$$

Proof. One can prove this in a quite similar way to the proof of the main result in [40]. An alternative proof is obtained using Proposition 4.5 and the same argument as in the proof of Theorem 1 in [41]. \square

Next we show that every map in $\Omega_{p,n}$ can be approximated the hyperbolic polynomial-like maps of type n .

Proposition 4.7. *Let $G \in \mathcal{W}$ be such that there exist domains \hat{U} and \hat{V} , whose boundaries are analytic Jordan curves, such that $\text{mod } \hat{V} \setminus \hat{U} > \epsilon_0/2$ and*

$$G: \hat{U} \rightarrow \hat{V}$$

is a real polynomial-like map of type n that is infinitely renormalizable with combinatorics bounded by p . Then there exist polynomial-like maps of type n

$$G_i: \hat{U}^i \rightarrow \hat{V}^i$$

such that

- A. *we have $\text{mod } \hat{V}^i \setminus \hat{U}^i \geq \epsilon_0/2$ and $G_i \in \mathcal{B}_{\text{nor}}(U)$,*
- B. *all critical points of G_i belong to the same periodic orbit,*
- C. *we have*

$$\lim_i |G_i - G|_{\mathcal{B}_{\text{nor}}(U)} = 0.$$

Proof. We will use the notation introduced in [40]. Let $\sigma = (\sigma_1, \sigma_2, \dots)$ be the combinatorics of G . By Proposition 2.2 in [40], there exists a sequence of polynomial P_i of type n with combinatorics $\sigma_i \star \dots \star \sigma_1$. By Corollary 2.3 in [40] any accumulation point of this sequence is a polynomial P of type n that is infinitely renormalizable with combinatorics σ . By the proof of Theorem 2 in [40] there is only one polynomial of type n with combinatorics σ , so the sequence P_i indeed converges to P . Indeed there are now far more general rigidity results for polynomials. See Kozlovski, Shen and van Strien [24][23].

Since P_i is a convergent sequence of polynomials of type n with connected Julia sets, it is possible to choose domains \hat{U}^i and \hat{V}^i such that

- $\inf_i \text{mod } \hat{V}^i \setminus \hat{U}^i > 0$,
- $P_i: \hat{U}^i \rightarrow \hat{V}^i$ is a polynomial-like map of type n .

and furthermore for some $K > 0$ there are K -quasiconformal maps

$$\phi_i: \mathbb{C}_n \rightarrow \mathbb{C}_n$$

such that

- $\phi_i(\hat{U}^i) = \hat{U}$ and $\phi_i(\hat{V}^i) = \hat{V}$,
- $\phi_i(\bar{z}) = \overline{\phi_i(z)}$,
- $P_i: \hat{U}^i \rightarrow \hat{V}^i$ is a polynomial-like map of type n ,
- $G \circ \phi_i = \phi_i \circ P_i$ on $\partial \hat{U}^i$.
- The sequence ϕ_i converges to a K -quasiconformal map ϕ .
- If $\hat{U}^\infty = \phi^{-1}(\hat{U})$ and $\hat{V}^\infty = \phi^{-1}(\hat{V})$ then $P: \hat{U}^\infty \rightarrow \hat{V}^\infty$ is a polynomial-like map of type n .

Let μ_i be the Beltrami field that coincides with $\mu_i = \bar{\partial}\phi_i/\partial\phi_i$ on $\mathbb{C}_n \setminus \hat{U}^i$, that is invariant under P_i , and $\mu_i = 0$ on $K(P_i)$. Let $\psi_i: \mathbb{C}_n \rightarrow \mathbb{C}_n$ be the unique quasiconformal map such that $\psi_i(-1, j) = (-1, j)$ and $\psi_i(0, j) = (0, j)$ for every j , and $\mu_i = \bar{\partial}\psi_i/\partial\psi_i$ on \mathbb{C}_n . Define

$$G_i = \psi_i \circ P_i \circ \psi_i^{-1}.$$

Then

$$G_i: \psi_i(\hat{U}^i) \rightarrow \psi_i(\hat{V}^i)$$

is a polynomial-like map of type n . Note that

$$\inf_i \text{mod } \psi_i(\hat{V}^i) \setminus \psi_i(\hat{U}^i) > 0.$$

Every subsequence of G_i has a convergent subsequence. Let F be one these accumulation points. We claim that $F = G$. Note that every accumulation point is of the form $F = \psi \circ P \circ \psi^{-1}$, where ψ is a K -quasiconformal map that is an accumulation point of the sequence ψ_i . We can assume, without loss of generality, that ϕ_i converges to a K -quasiconformal map ϕ .

Notice that

$$\phi_i \circ \psi_i^{-1} \circ G_i \circ \psi_i \circ \phi_i^{-1}(z) = \phi_i \circ P_i \circ \phi_i^{-1}(z) = G(z)$$

for $z \in \phi_i(\partial\hat{U}^i) = \partial\hat{U}$. Taking the limit on i we obtain

$$\phi \circ \psi^{-1} \circ F \circ \psi \circ \phi^{-1}(z) = G(z)$$

for $z \in \partial\hat{U}$. Moreover since $\psi_i \circ \phi_i^{-1}$ is conformal in $\mathbb{C}_n \setminus \hat{U}$ we conclude that $\psi \circ \phi^{-1}$ is conformal in $\mathbb{C}_n \setminus \hat{U}$. Since F and G are both infinitely renormalizable with the same combinatorics, one can use the Sullivan's pullback argument to conclude that there is quasiconformal conjugacy H between $F: \hat{U}^\infty \rightarrow \hat{V}^\infty$ and $G: \hat{U} \rightarrow \hat{V}$ such that H is conformal in $\mathbb{C}_n \setminus K(F)$. Since there are not invariant line fields supported of $K(F)$ we conclude that H is conformal on \mathbb{C}_n , so H is affine on each connected component of \mathbb{C}_n . Since $H(-1, j) = (-1, j)$ and $H(0, j) = (0, j)$ for every j , we conclude that H is the identity. So $F = G$ and G_i converges to G . Items A., B. and C. of Proposition 4.7 follows easily from this. \square

4.2. Vertical directions, codimension of E^h and vector bundles. Let $f: V_1 \rightarrow V_2$ be a polynomial-like map. Let \mathbb{B}_f be the vector space of the germs of holomorphic functions defined in a neighborhood of $K(f)$. We say that $v \in \mathbb{B}_f$ is a *vertical vector* if there exists a holomorphic vector field α defined on $\overline{\mathbb{C}} \setminus K(f)$ such that

$$(25) \quad v(x) = \alpha \circ f(x) - Df(x)\alpha(x)$$

for every x close to $K(f)$ and in the domain of α , and additionally

$$(26) \quad \lim_{z \rightarrow 0} z^2 \alpha(1/z) = 0.$$

We have an analogous definition for polynomial-like extended maps of type n . Denote the set of vertical directions of f as \hat{E}_f^v . Recall that $v \in \mathbb{B}_f$ is a *horizontal vector* ($v \in \hat{E}_f^h$) if there is quasiconformal vector field on \mathbb{C} such that (25) holds in a neighborhood of $K(f)$ and $\bar{\partial}\alpha = 0$ on $K(f)$. Lyubich [27] proved that

$$(27) \quad \mathbb{B}_f = \hat{E}_f^h + \hat{E}_f^v.$$

The same statement holds for polynomial-like extended maps of type n . Note that if $F \in \mathcal{W}$ has an extension that is a real polynomial-like extended map of type n and F is either infinitely renormalizable with bounded combinatorics in $\mathcal{C}_{p,n}$ or whose critical points belongs to the same periodic orbit then $E_F^h = \hat{E}_F^h \cap T\mathcal{B}_{nor}(U)$. Here E_F^h is as defined in Section 4.1.

Due the infinitesimal pullback argument, if f does not have invariant line fields on its Julia set $J(f)$ then $\hat{E}_f^h \cap \hat{E}_f^v$ is exactly the space of vectors v such that there

exists a vector field $\alpha(z) = az + b$ on $\overline{\mathbb{C}}$ that satisfies (25) in a neighborhood of $K(f)$. In particular if $F \in \Omega_{n,p}$ we have

$$T\mathcal{B}_{nor}(U) = E_F^h \oplus E_F^v.$$

Proposition 4.8. *If $f: V_1 \rightarrow V_2$ is a polynomial-like of degree d generated by the restriction of a polynomial of degree d then \hat{E}_f^v is exactly the linear space of polynomials of degree d . If f is a polynomial-like extended map of type n such that on each $\mathbb{C} \times \{i\}$ the map f coincides with a quadratic polynomial then \hat{E}_f^v is the space of vectors that coincides with quadratic polynomials on each $\mathbb{C} \times \{i\}$.*

Proof. Suppose that f is a polynomial of degree d and let $v \in \hat{E}_f^v$. Then the r.h.s. of (25) implies that v extends to an entire holomorphic function. Of course (26) implies that

$$|\alpha(y)| \leq C|y|$$

for some C , provided $y \in \mathbb{C}$ has large modulus. Since Df is a polynomial of degree $d - 1$ it follows from (25) that

$$|v(x)| \leq \tilde{C}|x|^d,$$

for some \tilde{C} , provided $|x|$ is large. So v is a polynomial whose degree is at most d . On the other hand, if v is a polynomial of degree at most d we have that $f_t = f + tv$ is a polynomial of degree d for every small t . Every f_t have the very same external class (see Lyubich [27]). This implies that $v = \partial_t f_t|_{t=0} \in \hat{E}_f^v$. The proof in the case of a polynomial-like extended map of type n is analogous. \square

The following is similar to Lyubich [27, Lemma 4.10], but for the sake of completeness we provide details.

Proposition 4.9. *Let $F: W \rightarrow V$ be a polynomial-like map of type n with connected Julia set satisfying*

- i. $0 < \epsilon_0 < \text{mod}(V \setminus W) < \epsilon_1$,
- ii. $\text{diam } K(F) \cap (\mathbb{C} \times \{i\}) \geq 1$ for every i ,
- iii. $\text{diam } V \cap (\mathbb{C} \times \{i\}) \leq C_1$ for every i .

Let $v \in E_F^v \cap \mathcal{B}(W)$. Consider the holomorphic vector field

$$\alpha: \overline{\mathbb{C}}_n \setminus K(F) \rightarrow \mathbb{C}$$

such that $\lim_{z \rightarrow 0} z^2 \alpha(1/z) = 0$ and

$$v(z) = \alpha(F(z)) - DF(z)\alpha(z)$$

for every $z \in W \setminus K(F)$. Then there is $C_2 > 0$, that depends only on ϵ_0 , ϵ_1 and C_1 , such that

$$|\alpha|_{sph} \overline{\mathbb{C}}_n \setminus F^{-1}W \leq C_2 |v|_{\mathcal{B}(W)}.$$

Here $|\cdot|_{sph} Q$ denotes the sup norm on Q considering the spherical metric on each component of $\overline{\mathbb{C}}_n$.

Proof. Define $K_i(F) = K(F) \cap (\mathbb{C} \times \{i\})$, $1 \leq i \leq n$. Let

$$\phi_i: (\overline{\mathbb{C}} \times \{i\}) \setminus K_i(F) \rightarrow \mathbb{D} \times \{i\}$$

be conformal maps such that $\phi_i(\infty, i) = (0, i)$. Define the conformal maps

$$\phi: \overline{\mathbb{C}}_n \setminus K(F) \rightarrow \mathbb{D} \times \{1, \dots, n\}$$

as $\phi(z, i) = \phi_i(z, i)$. Define

$$\tilde{W} = \phi(W \setminus K(F)), \tilde{V} = \phi(V \setminus K(F))$$

and

$$\tilde{F}: \tilde{W} \rightarrow \tilde{V}$$

as

$$\tilde{F}(z, i) = \phi \circ F \circ \phi^{-1}(z, i).$$

Let $\psi(x, i) = (z/|z|^2, i)$, $\hat{W} = \overline{\tilde{W} \cup \psi(\tilde{W})}$ and $\hat{V} = \overline{\tilde{V} \cup \psi(\tilde{V})}$. Then \tilde{F} has a analytic extension to a covering

$$\hat{F}: \hat{W} \rightarrow \hat{V}$$

satisfying $\hat{F}(\mathbb{S} \times \{1, \dots, n\}) = \mathbb{S} \times \{1, \dots, n\}$. Note that each connected component of

$$\hat{V} \setminus \hat{W}$$

is an annulus with modulus larger than ϵ_0 . This implies that there is k (that depends only on $\epsilon_0, \epsilon_1, C_1$ and n) such that

$$|D\hat{F}^{kn}(z, i)| \geq 2$$

for every $(z, i) \in \hat{F}^{-(kn+1)}\hat{W}$. Note that there is $C_3 > 1$, that depends only on $\epsilon_0, \epsilon_1, C_1$, such that

- $|D\phi(z, i)| \in [1/C_3, C_3]$ for every $(z, i) \in W \setminus F^{-(kn+1)}W$,
- $|DF(z, i)| \in [1/C_3, C_3]$ for every $(z, i) \in F^{-1}W \setminus F^{-(kn+1)}W$,
- $|D\hat{F}(z, i)| \in [1/C_3, C_3]$ for every $(z, i) \in \hat{F}^{-1}\hat{W} \setminus \hat{F}^{-(kn+1)}\hat{W}$.
- We have $1/C_3 \leq |z| \leq C_3$ for every $z \in \partial F^{-1}W$.

Define

$$\hat{\alpha}: \mathbb{D} \times \{1, \dots, n\} \rightarrow \mathbb{C}$$

as

$$\hat{\alpha}(z, i) = D\phi(\phi^{-1}(z, i))\alpha(\phi^{-1}(z, i))$$

and

$$\hat{v}(z, i) = D\phi(F(\phi^{-1}(z, i)))v(\phi^{-1}(z, i)).$$

Then $\hat{\alpha}(0) = 0$,

$$\hat{v} = \hat{\alpha} \circ \hat{F} - D\hat{F} \cdot \hat{\alpha},$$

and consequently

$$\sum_{j=0}^{nk} D\hat{F}^{nk-j}(\hat{F}^{j+1}(z, i))\hat{v}(\hat{F}^j(z, i)) = \hat{\alpha} \circ \hat{F}^{nk}(z, i) - D\hat{F}^{nk}(z, i) \cdot \hat{\alpha}(z, i).$$

for $(z, i) \in \partial \hat{F}^{-(kn+1)}\hat{W}$. Let (z_0, i_0) be such that

$$|\hat{\alpha}(z_0, i_0)| = \max_{(z, i) \in \partial \hat{F}^{-(kn+1)}\hat{W}} |\hat{\alpha}(z, i)|.$$

Then

$$\left| \sum_{j=0}^{nk} D\hat{F}^{nk-j}(\hat{F}^{j+1}(z, i))\hat{v}(\hat{F}^j(z_0, i_0)) \right| \geq 2 \max_{(z, i) \in \partial \hat{F}^{-(kn+1)}\hat{W}} |\hat{\alpha}(z, i)| - \max_{(z, i) \in \partial \hat{F}^{-1}\hat{W}} |\hat{\alpha}(z, i)|.$$

Since $\hat{\alpha}$ is holomorphic the maximum principle implies

$$\max_{(z, i) \in \partial \hat{F}^{-(kn+1)}\hat{W}} |\hat{\alpha}(z, i)| \geq \max_{(z, i) \in \partial \hat{F}^{-1}\hat{W}} |\hat{\alpha}(z, i)|,$$

so

$$\max_{(z,i) \in \partial \hat{F}^{-(kn+1)} \tilde{W}} |\hat{\alpha}(z,i)| \leq C_4 \sup_{(z,i) \in \hat{F}^{-1} \tilde{W} \setminus \hat{F}^{-(kn+1)} \tilde{W}} |\hat{v}(z,i)|.$$

Here $C_4 = nkC_3^{mk}$. Consequently

$$\begin{aligned} \max_{(z,i) \in \partial F^{-1} W} |\alpha(z,i)| &\leq C_3 \max_{(z,i) \in \partial \hat{F}^{-1} \tilde{W}} |\hat{\alpha}(z,i)| \\ &\leq C_3 \max_{(z,i) \in \partial \hat{F}^{-(kn+1)} \tilde{W}} |\hat{\alpha}(z,i)| \\ &\leq C_3 C_4 \max_{(z,i) \in \hat{F}^{-1} \tilde{W} \setminus \hat{F}^{-(kn+1)} \tilde{W}} |\hat{v}(z,i)| \\ &\leq C_3^2 C_4 \max_{(z,i) \in F^{-1} W \setminus F^{-(kn+1)} W} |v(z,i)| \\ &\leq C_3^2 C_4 \max_{(z,i) \in F^{-1} W} |v(z,i)|. \end{aligned}$$

Note that

$$\begin{aligned} \sup_{(z,i) \in \overline{\mathbb{C}}_n \setminus F^{-1} W} |\alpha(z,i)|_{sph} \overline{\mathbb{C}} &= \sup_{(z,i) \in \overline{\mathbb{C}}_n \setminus F^{-1} W} \frac{2|\alpha(z,i)|}{1+|z|^2} \\ &\leq \sup_{(z,i) \in \overline{\mathbb{C}}_n \setminus F^{-1} W} \left| \frac{2\alpha(z,i)}{z^2} \right| \\ &\leq \max_{(z,i) \in \partial F^{-1} W} \left| \frac{2\alpha(z,i)}{z^2} \right| \\ &\leq C_3^2 \max_{(z,i) \in \partial F^{-1} W} |\alpha(z,i)|. \end{aligned}$$

□

Proposition 4.10 (Codimension of E_G^h). *For every $G \in \Omega_{n,p}$ the codimension of E_G^h is n .*

Proof. By Proposition 4.7 for every $G \in \Omega_{n,p}$ one can find a polynomial-like extension $G: \tilde{U} \rightarrow \tilde{V}$ of type n and a sequence of polynomial-like maps $G_i: \hat{U}^i \rightarrow \hat{V}^i$ of type n whose periodic points belongs to the same critical orbit and such that U is compactly contained in \tilde{U}^i and \tilde{U}^i is compactly contained in \tilde{U} . Denote $E_{G_i}^j(\tilde{U}) = \hat{E}_{G_i}^j \cap T\mathcal{B}_{nor}(\tilde{U})$, where $j \in \{v, h\}$. We claim that $\text{codim } E_{G_i}^h(\tilde{U}) = n$.

Indeed for each $q \in C(G_i)$, let $m_q^i > 0$ be such that $G_i^{m_q^i}(q) \in C(G_i)$ and $G_i^k(q) \notin C(G_i)$ for every $0 < k < m_q^i$. Given $v \in T\mathcal{B}_{nor}(U)$, let $v_{q,k} = v(G_i^k(q))$. Then there is a unique solution $\{\alpha_{q,k}\}_{q \in C(G_i), 1 \leq k \leq m_q^i}$ for the homogeneous system of linear equations

$$v_{q,k} = \alpha_{q,k+1} - DG_i(G_i^k(q)) \cdot \alpha_{q,k}, \quad 1 \leq k < m_q^i, \quad q \in C(G_i),$$

$$v_{q,0} = \alpha_{q,1}, \quad q \in C(G_i).$$

In particular

$$(v_{q,k})_{q \in C(G_i), 0 \leq k < m_q^i} \mapsto (\alpha_{q,k})_{q \in C(G_i), 1 \leq k \leq m_q^i}$$

is a linear bijection. Note that $v \in E_{G_i}^h$ if and only if $\alpha_{q,m_q^i} = 0$ for every $q \in C(G_i)$, that is, if and only if v belongs to the kernel of the linear map

$$v \mapsto (\alpha_{q,m_q^i})_{q \in C(G_i)}.$$

Since

$$v \mapsto (v_{q,k})_{q \in C(G_i), 0 \leq k < m_q^i}$$

and

$$(v_{q,k})_{q \in C(G_i), 0 \leq k < m_q^i} \mapsto (\alpha_{q,m_q^i})_{q \in C(G_i)}$$

are onto continuous linear maps it follows that $\text{codim } E_{G_i}^h(\tilde{U}) = n$ (Recall that G_i has n critical points). So $\dim E_{G_i}^v(\tilde{U}) = n$. Since \tilde{U} is compatible with G , we have that [42, Proposition 10.4] implies $\dim E_G^v(\tilde{U}) = \text{codim } E_G^h(\tilde{U}) = n$.

Unfortunately U is not compatible with G (the repelling fixed point -1 of G does not belong to the interior of U), so we need to be a little more careful to conclude that $\text{codim } E_G^h = n$. Consider the natural affine inclusion

$$\pi: \mathcal{B}_{\text{nor}}(\tilde{U}) \rightarrow \mathcal{B}_{\text{nor}}(U)$$

Then $D\pi$ is continuous, injective map, it has dense image and moreover

$$(D\pi)^{-1}E_G^h = E_G^h(\tilde{U}).$$

Note that if $\text{codim } E_G^h \geq k$ then there is a bounded linear onto map $\psi: T_G \mathcal{B}_{\text{nor}}(U) \rightarrow \mathbb{R}^k$ such that $E_G^h \subset \text{Ker } \psi$. Since $D\pi$ have dense image we have that $\psi \circ D\pi$ is also a bounded linear onto map such that $E_G^h(\tilde{U}) \subset \text{Ker } \psi \circ D\pi$, so $\text{codim } E_G^h(\tilde{U}) \geq \text{codim } \text{Ker } \psi \circ D\pi = k$. So $\text{codim } E_G^h \leq \text{codim } E_G^h(\tilde{U}) = n$.

On the other hand, since π is injective we have that $\dim \pi(E_G^v(\tilde{U})) = n$. If $v \in \pi(E_G^v(\tilde{U})) \cap E_G^h$ then $v \in E_G^v(\tilde{U}) \cap E_G^h(\tilde{U}) = \{0\}$. So $\text{codim } E_G^h \geq n$. \square

The following lemma is elementary. We included it here for the sake of completeness.

Lemma 4.11. *Let $(\mathcal{B}_i, |\cdot|_i)$, $i = 1, 2$, be Banach spaces. Let Ω be a compact metric space and suppose that for every $f \in \Omega$ we associate vector subspaces $E_f^v \subset \mathcal{B}_2 \subset \mathcal{B}_1$, $E_{f,i}^h \subset \mathcal{B}_i$ satisfying*

- A. *For every $f \in \Omega$ we have $\mathcal{B}_2 = E_f^v \oplus E_{f,2}^h$ and $E_f^v \cap E_{f,1}^h = \{0\}$.*
- B. *The set*

$$\{(f, v): f \in \Omega, v \in E_{f,i}^h\}$$

is a closed subset of $\Omega \times \mathcal{B}_i$.

- C. *We have that*

$$\{(f, v): f \in \Omega, v \in E_f^v, |v|_i \leq 1\}$$

is a compact subset of $\Omega \times \mathcal{B}_i$, $i = 1, 2$.

- D. *There exists $n \in \mathbb{N}$ such that $\dim E_f^v = n$ for every $f \in \Omega$.*
- E. *The inclusion $\iota: \mathcal{B}_2 \rightarrow \mathcal{B}_1$ is a compact linear operator and*

$$\iota^{-1}(E_{f,1}^h) = E_{f,2}^h.$$

Then

- I. *The set*

$$E^v = \{(f, v): f \in \Omega, v \in E_f^v\},$$

with the topology induced by $\Omega \times \mathcal{B}_2$, is a topological vector bundle (with the obvious linear structure on the fibers E_f^v) with fibers of dimension n .

- II. Let \sim be the equivalent relation on $\Omega \times \mathcal{B}_2$ defined by $(f, v) \sim (g, w)$ if and only if $f = g$ and $v - w \in E_f^h$. Then the quotient topological space

$$E = \{(f, [v]) \text{ s.t. } f \in \Omega \text{ and } [v] \in \mathcal{B}/E_{f,2}^h\}.$$

is a topological vector bundle with fibers of dimension n .

- III. Define

$$|(f, [v])| = \text{dist}_{\mathcal{B}_2}(v, E_{f,2}^h) = \inf\{|v - w|_2 : w \in E_{f,2}^h\}.$$

then

$$(f, [v]) \in E \mapsto |(f, [v])|_2$$

is continuous.

Proof of I. All limits in the proof of I. and II are in the topology of $(\mathcal{B}_2, |\cdot|_2)$. Let $u \in \mathcal{B}_2$. Then for every $g \in \Omega$ there are unique vectors $v^{g,u} \in E_g^v$ and $w^{g,u} \in E_{g,2}^h$ such that

$$u = v^{g,u} + w^{g,u}.$$

First note that

$$(28) \quad \sup \{|v^{g,u}|_2, g \in \Omega, |u|_2 \leq 1\} \cup \{|w^{g,u}|_2, g \in \Omega, |u|_2 \leq 1\} < \infty.$$

Otherwise there is a sequence $g_i \in \Omega$, $|u_i| \leq 1$ such that

$$r_i = \max\{|v^{g_i, u_i}|_2, |w^{g_i, u_i}|_2\} \rightarrow_i \infty.$$

Since Ω is compact, without loss of generality we can assume that

$$\lim_i g_i = g \in \Omega$$

and C. implies that we can assume

$$\lim_i \frac{v^{g_i, u_i}}{r_i} = v \in E_g^v.$$

and consequently

$$(29) \quad \lim_i \frac{w^{g_i, u_i}}{r_i} = -v.$$

On the other hand by (29) and B. we have $v \in E_g^h$, so by A. we conclude $v = 0$. This is a contradiction with the definition of r_i . So (28) holds. We claim that the map

$$S: \Omega \times \mathcal{B}_2 \rightarrow \Omega \times \mathcal{B}_2$$

defined by

$$S(g, u) = (g, v^{g,u}) \in \mathcal{B}_2$$

is a continuous linear map. Indeed suppose $\lim_i g_i = g$ and $\lim_i u_i = u$. By assumption C. and (28), taking a subsequence we may assume that

$$\lim_i v^{g_i, u_i} = v \in E_g^v$$

and consequently by B.

$$\lim_i w^{g_i, u_i} = \lim_i u_i - \lim_i v^{g_i, u_i} = u - v \in E_{g,2}^h$$

By A. we conclude that $v = v^{g,u}$ and $u - v = w^{g,u}$. This proves the claim. Let $f \in \Omega$ and choose a basis $v_1, \dots, v_n \in E_f^v$. Let $v_i^g = S(g, v_i) \in E_g^v$ and $w_i^g = v_i - S(g, v_i) \in E_{g,2}^h$, with $g \in \Omega$. Of course

$$v_i = v_i^g + w_i^g.$$

So for every i we have that $g \mapsto v_i^g$ is continuous and moreover $v_i^f = v_i$ and $w_i^f = 0$. In particular there exists an open neighborhood O_1 of f in Ω such that $\{v_i^g\}_i$ is a basis of E_g^v for every $g \in O$.

Reducing the neighborhood O , we may assume that $E_{g,2}^h \cap E_f^v = \{0\}$ for every $g \in O$. Otherwise it would exist a sequence $g_i \rightarrow_i f$ and $w_i \in E_{g_i,2}^h \cap E_f^v$ satisfying $|w_i| = 1$. By D. we may assume $\lim_i w_i = w \in E_f^v$. By B. we have $w \in E_{f,2}^h$, which contradicts A.

Define the map

$$H: O \times E_f^v \rightarrow \{(g, v): g \in O, v \in E_g^v\}$$

as

$$H(g, \sum_i c_i v_i) = (g, \sum_i c_i v_i^g).$$

We have that H is a continuous and bijective map. Note that

$$H^{-1}(g, u) = (g, v),$$

where v is the only vector in $E_{f,2}^h$ such that $v - u \in E_{g,2}^h$.

We claim that H^{-1} is continuous. Indeed, suppose that $\lim_i (g_i, u_i) = (g, u)$, with $g, g_i \in O$ and $u, u_i \in E_{g_i}^v$. If $H^{-1}(g_i, u_i) = (g_i, v_i)$ then $w_i = v_i - u_i \in E_{g_i,2}^h$ and $v_i \in E_{g_i}^v$. Let $r_i = \max\{|v_i|_2, |w_i|_2\}$. We claim that

$$(30) \quad \sup_i r_i < \infty.$$

Otherwise without loss of generality we may assume $\lim_i r_i = \infty$. By D. we may assume that $\lim_i v_i/r_i = \tilde{v} \in E_f^v$ and consequently $\lim_i w_i/r_i = \tilde{v}$. By B. we have $\tilde{v} \in E_{f,2}^h$. So $\tilde{v} = 0$, in contradiction with the definition of r_i . This proves (30). In particular without loss of generality we can assume $\lim_i v_i = \hat{v} \in E_f^v$ and consequently by B. we have $\lim_i w_i = \hat{w} = \hat{v} - u \in E_{f,2}^h$. In particular $H^{-1}(g, u) = (g, \hat{v})$. So H^{-1} is continuous. So

$$\hat{H}: O \times \mathbb{R}^n \rightarrow \{(g, v): g \in O, v \in E_g^v\}$$

defined by

$$\hat{H}(g, (c_i)_i) = (g, \sum_i c_i v_i^g)$$

is a local trivialization of the vector bundle E^v in the open set $\{(g, v): g \in O, v \in E_g^v\}$. \square

Proof of II. Let $\pi: \Omega \times \mathcal{B}_2 \rightarrow E$ be a natural projection

$$(f, v) \mapsto (f, [v]_f),$$

where $[v]_f$ represents the equivalent class of v in $\mathcal{B}/E_{f,2}^h$. We will define a homeomorphism

$$T: E^v \rightarrow E$$

that is a vector bundle homeomorphism. Indeed let T be the restriction of π to E^v . Of course T is a continuous map that preserves the linear structure in the fibers. It is also a bijection, since $T(f, v) = T(g, w)$ implies $f = g$, with $v, w \in E_f^v$ and $v - w \in E_{f,2}^h$, so by A. we have $v = w$. Note that $T^{-1}(f, [u]_f) = (f, v)$, where v is the unique vector that satisfies $v \in E_f^v$ and $u - v \in E_{f,2}^h$. Note that

$T^{-1}(f, [u]_f) = S(f, u)$, where S was defined in the proof of I. Consequently T^{-1} is continuous, since S descends to the quotient space E as T^{-1} . \square

Proof of III. We claim that

$$(31) \quad (f, v) \in \Omega \times \mathcal{B}_2 \rightarrow \text{dist}_{\mathcal{B}_2}(v, E_f^h)$$

is continuous. Indeed suppose that $\lim_k (f_k, v_k) = (f, v)$. We have

$$|\text{dist}_{\mathcal{B}_2}(v_k, E_{f_k,2}^h) - \text{dist}_{\mathcal{B}_2}(v, E_{f_k,2}^h)| \leq \text{dist}_{\mathcal{B}_2}(v_k - v, E_{f_k,2}^h) \leq |v - v_k|_2 \rightarrow_k 0,$$

in particular

$$\lim_k \text{dist}_{\mathcal{B}_2}(v_k, E_{f_k,2}^h) - \text{dist}_{\mathcal{B}_2}(v, E_{f_k,2}^h) = 0,$$

so to prove the claim it is enough to show that

$$(32) \quad \lim_k \text{dist}_{\mathcal{B}_2}(v, E_{f_k,2}^h) = \text{dist}_{\mathcal{B}_2}(v, E_f^h).$$

Fix $\epsilon > 0$ and let $w \in E_{f,2}^h$ be such that

$$|v - w|_2 < \text{dist}_{\mathcal{B}_2}(v, E_{f,2}^h) + \epsilon.$$

Then $\lim_k S(f_k, w) = 0$, where S is as defined in the proof of I. In particular $w_k = w - S(f_k, w) \in E_{f_k,2}^h$ and for large k we have $|v - w_k| < \text{dist}_{\mathcal{B}_2}(v, E_{f,2}^h) + 2\epsilon$. Since $\epsilon > 0$ is arbitrary

$$\limsup_k \text{dist}_{\mathcal{B}_2}(v, E_{f_k,2}^h) \leq \text{dist}_{\mathcal{B}_2}(v, E_{f,2}^h).$$

On the other hand, if

$$\liminf_k \text{dist}_{\mathcal{B}_2}(v, E_{f_k,2}^h) \leq \text{dist}_{\mathcal{B}_2}(v, E_{f,2}^h) - 2\epsilon$$

then we can assume (taking a subsequence) that there is $w_k \in E_{f_k,2}^h$ such that

$$|v - w_k|_2 \leq \text{dist}_{\mathcal{B}_2}(v, E_{f,2}^h) - \epsilon.$$

Let $u_k = S(f, w_k) \in E_{f,2}^v$. Note that $\sup_k |w_k|_2 < \infty$, which implies $\sup_k |u_k|_2 < \infty$ and consequently $y_k = w_k - u_k \in E_{f,2}^h$ satisfies

$$\sup_k |y_k|_2 < \infty.$$

By B. and E. we can find $y \in E_{f,1}^h$ and a subsequence of y_k such that y_k converges to y in \mathcal{B}_1 . Taking a subsequence we can assume that $\lim_k u_k = u \in E_f^v$ (in the topologies of \mathcal{B}_i , $i = 1, 2$). So w_k converges to $u + y$ in \mathcal{B}_1 . By A., B. and E. we have $u = 0$. We conclude that

$$\text{dist}_{\mathcal{B}_2}(v, E_{f,2}^h) \leq \liminf_k |v - y_k|_2 \leq \text{dist}_{\mathcal{B}_2}(v, E_{f,2}^h) - \epsilon,$$

which is a contradiction. So (32) holds. This proves the claim. Since $(f, v) \sim (g, \tilde{v})$ implies $\text{dist}_{\mathcal{B}_2}(v, E_f^h) = \text{dist}_{\mathcal{B}_2}(\tilde{v}, E_g^h)$ the function (31) descends to the quotient topological space E as a continuous function. \square

Proposition 4.4 implies that

$$\{(F, v), F \in \Omega_{n,p} \text{ and } v \in E_F^h\}$$

is a closed subset of $\Omega_{n,p} \times T\mathcal{B}_{nor}(U)$. We also have

Lemma 4.12. *The set*

$$(33) \quad \mathcal{E} = \{(F, v), F \in \Omega_{n,p} \text{ and } v \in E_F^v, |v|_{T\mathcal{B}_{nor}(U)} \leq 1\}$$

is a compact subset of $\Omega_{n,p} \times T\mathcal{B}_{nor}(U)$.

Proof. Let (F_k, v_k) be a sequence in the set \mathcal{E} . Due the complex bounds there exist domains $W_k, V_k \in \mathbb{C}_n$ such that $\overline{W_k} \subset V_k$ and

$$F_k: W_k \rightarrow V_k$$

are polynomial-like maps of type n satisfying

$$\text{mod}(V_k \setminus W_k) \geq \epsilon_0.$$

Using the same argument as McMullen [31, Theorem 5.8] there is a polynomial-like map of type n $F: W \rightarrow V$ with $\text{mod}(V \setminus W) \geq \epsilon_0$ such that $\lim_k F_k = F$ in the topology defined by McMullen. In particular $\lim_k W_k = W$ and $\lim_k V_k = V$ in the Carathéodory topology and F_k converges to F uniformly on compact subsets of W . Consequently $\lim_k F_k = F$ in $\mathcal{B}_{nor}(U)$ and we can find \tilde{V} compactly contained in V such that

$$F_k: F_k^{-1}\tilde{V} \rightarrow \tilde{V}$$

are polynomial-like maps of type n satisfying

$$\text{mod}(\tilde{V} \setminus F_k^{-1}\tilde{V}) \geq \epsilon_0/2.$$

Let $\tilde{W} = F^{-1}\tilde{V}$. Since $v_k \in E_{F_k}^v$ there exist holomorphic vectors fields

$$\alpha_k: \overline{\mathbb{C}_n} \setminus K(F_k) \rightarrow \mathbb{C}$$

such that $\alpha_k(\infty) = 0$ and

$$v_k(z) = \alpha_k(F_k(z)) - DF_k(z)\alpha_k(z)$$

for every $z \in W_k \setminus K(F_k)$.

Finally, for every large $j > 0$ it is possible to find a domain V^j such that

$$K(F) \subset V^j \subset \overline{\{z \in \mathbb{C}_n: \text{dist}(z, K(F)) < 1/j\}} \subset \tilde{V}$$

and

$$F: F^{-1}V^j \rightarrow V^j$$

is a polynomial-like map of type n . Consequently there is $k_0 = k_0(j)$ such that for every $k \geq k_0$ we have that

$$F_k: F_k^{-1}V^j \rightarrow V^j$$

is a polynomial-like map of type n . Note that $F_k^{-1}V^j \subset \tilde{W}$ for large k . Due Proposition 4.9 we have that

$$|\alpha_k|_{sph} \overline{\mathbb{C}_n} \setminus F_k^{-2}V^j \leq C_j |v_k|_{\mathcal{B}(V^j)} \leq C_j |v_k|_{\mathcal{B}(\tilde{W})}.$$

for large k . We claim that

$$(34) \quad \sup_k |v_k|_{\mathcal{B}(\tilde{W})} < \infty.$$

Indeed, otherwise we may assume that $r_k = |v_k|_{\mathcal{B}(\tilde{W})}$ diverges to infinity. Then $\hat{\alpha}_k = \alpha_k/r_k$ satisfies

$$|\hat{\alpha}_k|_{sph} \overline{\mathbb{C}_n} \setminus F_k^{-2}V^j \leq C_j$$

This implies that a subsequence of $\hat{\alpha}_k$ converges uniformly on compact subsets of $\mathbb{C}_n \setminus K(F)$ to a holomorphic vector field $\hat{\alpha}: \mathbb{C}_n \setminus K(F) \rightarrow \mathbb{C}$ and the corresponding

subsequence of $\hat{v}_k = v_k/r_k$ converges uniformly on compact subsets of $W \setminus K(F)$ to

$$\hat{v} = \hat{\alpha} \circ F - DF \cdot \hat{\alpha}.$$

By the maximum principle we have that \hat{v}_k is a uniform Cauchy sequence on compact subsets of W , so \hat{v} extends to a holomorphic function on W and $\lim_k \hat{v}_k = \hat{v}$ uniformly on compact subsets of W . Since $|\hat{v}_k|_{\mathcal{B}(\tilde{W})} = 1$ for every k we have $|\hat{v}|_{\mathcal{B}(\tilde{W})} = 1$. On the other hand

$$|\hat{v}|_{\mathcal{B}(U)} = \lim_k |\hat{v}_k|_{\mathcal{B}(U)} = \lim_k 1/r_k = 0,$$

so $\hat{v} = 0$ everywhere, in contradiction with $|\hat{v}|_{\mathcal{B}(\tilde{W})} = 1$. This proves the claim.

Now we can use the same argument as in the previous paragraph to conclude that there is a subsequence of α_k that converges uniformly on compact subsets of $\mathbb{C}_n \setminus K(F)$ to a holomorphic vector field $\alpha: \overline{\mathbb{C}_n} \setminus K(F) \rightarrow \mathbb{C}$ and the corresponding subsequence of v_k converges in $\mathcal{B}(\tilde{W})$ (and in particular in $\mathcal{B}(U)$) so a vector v that satisfies

$$v = \alpha \circ F - Df \cdot \alpha$$

on $W \setminus K(F)$. This concludes the proof. \square

As an immediate consequence of Lemmas 4.11 and 4.12 we have

Proposition 4.13. *The quotient topological space*

$$E = \{(F, [v]) \text{ s.t. } F \in \Omega_{n,p} \text{ and } [v] \in T\mathcal{B}_{nor}(U)/E_F^h\}.$$

is a topological vector bundle with fibers of dimension n . Moreover

$$(35) \quad (F, [v]) \mapsto |(F, [v])| = \text{dist}_{T\mathcal{B}_{nor}(U)}(v, E_F^h)$$

is a continuous function.

Proof. Let \hat{U} be a symmetric domain with respect to the real trace of \mathbb{C}_n , that is compactly contained in the interior of U , such that the $\hat{U} \cap \mathbb{R}$ is an interval that contain in its interior the convex closure of the postcritical set of every $F \in \Omega_{n,p}$. Let $\mathcal{B}_2 = T\mathcal{B}_{nor}(U)$, $\mathcal{B}_1 = \mathcal{B}(\hat{U})$, $E_{F,2}^h = E_F^h$ and $E_{F,1}^h$ be the set of horizontal vectors of $\mathcal{B}(\hat{U})$. Apply Lemma 4.11. \square

5. HYPERBOLICITY OF THE ω -LIMIT SET $\Omega_{n,p}$ OF \mathcal{R} .

Given $F \in \Omega_{n,p}$, denote

$$\mathfrak{B}_+(F) = \{v \in T_F\mathcal{B}_{nor}(U) \text{ s.t. } \sup_{i \in \mathbb{N}} |D\mathcal{R}_f^i \cdot v_i| < \infty\}.$$

Recall we choose $U = D_{\delta_0, \theta_0}$. The goal of this section is to prove

Proposition 5.1. *Suppose that for every $F \in \Omega_{n,p}$ we have*

$$(36) \quad \mathfrak{B}_+(F) \subset E_F^h.$$

Then $\Omega_{n,p}$ is a hyperbolic set. Moreover its stable direction is exactly E^h .

Proposition 5.1 reduces the study of the hyperbolicity of $\Omega_{n,p}$ to the study of the existence and regularity of the solutions α of the cohomological equation (16). So to show that $\Omega_{n,p}$ is a hyperbolic set it remains to prove

Theorem 4 (Key Lemma). *If $F \in \Omega_{n,p}$ then*

$$(37) \quad \mathfrak{B}_+(F) \subset E_F^h.$$

We will prove Theorem 4 in Section 8. As an immediate consequence of Proposition 5.1 and Theorem 4 we have

Theorem 5 (Theorem B). $\Omega_{n,p}$ is a hyperbolic set. Moreover its stable direction is exactly E^h .

5.1. A criterium for hyperbolicity of cocycles. Let E be a topological vector bundle with base Ω and fiber \mathbb{R}^n and projection $p: E \rightarrow \Omega$. We denote elements of E by (x, v) , where $x \in \Omega$ and $v \in p^{-1}(x)$. We also assume that Ω is compact. Additionally, assume that $|\cdot|$ is a continuous function

$$(x, v) \in E \mapsto |(x, v)| \in \mathbb{R}$$

so that $|\cdot|$ is a norm on each fiber $p^{-1}(x)$. We will abuse the notation writing $|v|$ instead of $|(x, v)|$.

Let $L: E \rightarrow E$ be a fiber-preserving homeomorphism that is linear on the fibers. The map L is called a linear cocycle on E . Define

$$\mathfrak{B}_+ = \{(x, v) \in E \text{ s.t. } \sup_{i \in \mathbb{N}} |v_i| < \infty, \text{ where } L^i(x, v) = (x_i, v_i)\}.$$

$$\mathfrak{B} = \{(x, v) \in E \text{ s.t. } \sup_{i \in \mathbb{Z}} |v_i| < \infty, \text{ where } L^i(x, v) = (x_i, v_i)\}.$$

$$\mathcal{S} = \{(x, v) \in E \text{ s.t. } \lim_{i \rightarrow +\infty} |v_i| = 0, \text{ where } L^i(x, v) = (x_i, v_i)\}.$$

$$\mathcal{U} = \{(x, v) \in E \text{ s.t. } \lim_{i \rightarrow -\infty} |v_i| = 0, \text{ where } L^i(x, v) = (x_i, v_i)\}.$$

and the zero section

$$E_0 = \{(x, 0) \in E\}.$$

We say that the cocycle L is uniformly expanding if there exist $K > 0$ and $\theta > 1$ such that for every $(x, v) \in E$ we have

$$(38) \quad |v_i| \geq K\theta^i |v|$$

for every $i \geq 0$, where $L^i(x, v) = (x_i, v_i)$.

Proposition 5.2. *The cocycle $L: E \rightarrow E$ is uniformly expanding if and only if*

$$(39) \quad \mathfrak{B}_+ = E_0.$$

Proof. Of course if $L: E \rightarrow E$ is uniformly expanding then (39) holds. To prove the reverse implication, note that (39) implies $\mathcal{S} = \mathfrak{B} = E_0$. By Theorem 2 in Sacker and Sell [35] (see also Section 7 there) we have that $L: E \rightarrow E$ is uniformly expanding. \square

One can also prove Proposition 5.2 applying Sacker and Sell's results in [36, Lemma 9 and Theorem 2]. We just refer to that because the proof of these results in [36] seems to be more elementary than the proof of Theorem 2 in [35].

5.2. **Unstable invariant cones.** Let $F \in \Omega_{n,p}$, Denote

$$\mathfrak{B}_+(F) = \{v \in T_F \mathcal{B}_{nor}(U) \text{ s.t. } \sup_{i \in \mathbb{N}} |D\mathcal{R}_f^i \cdot v_i| < \infty\}.$$

Consider the topological vector bundle E (see Proposition 4.13)

$$E = \{(F, [v]) \text{ s.t. } F \in \Omega_{n,p} \text{ and } [v] \in T_F \mathcal{B}_{nor}(U)/E_F^h\}.$$

with the continuous function (35) that restricted to each $T_F \mathcal{B}_{nor}(U)/E_F^h$ is the usual quotient norm. Recall that due Proposition 4.13 we have that

$$\dim T_F \mathcal{B}_{nor}(U)/E_F^h = n.$$

By Proposition 4.2 the linear transformation

$$(40) \quad D\mathcal{R}_F: T_F \mathcal{B}_{nor}(U) \rightarrow T_{\mathcal{R}F} \mathcal{B}_{nor}(U)$$

induces a bounded linear transformation

$$L_F: T_F \mathcal{B}_{nor}/E_F^h \rightarrow T_{\mathcal{R}F} \mathcal{B}_{nor}(U)/E_{\mathcal{R}F}^h.$$

Lemma 5.3. *The map*

$$L(F, v) = (\mathcal{R}F, L_F \cdot v)$$

is a vector bundle isomorphism in the vector bundle E , that is, it is a homeomorphism of E onto itself that preserves the linear structure on the fibers.

Proof. Let $\pi: \Omega_{n,p} \times T\mathcal{B}_{nor}(U) \rightarrow E$ be a natural projection

$$(F, v) \mapsto (F, [v]_F),$$

where $[v]_F$ represents the equivalent class of v in $T\mathcal{B}_{nor}(U)/E_F^h$. Of course

$$\tilde{L}: \Omega_{n,p} \times T\mathcal{B}_{nor}(U) \rightarrow E$$

defined by $\tilde{L}(F, v) = \pi(\mathcal{R}F, D\mathcal{R}_F \cdot v)$ is continuous. Then by Proposition 4.2 the map \tilde{L} descends to the topological quotient space E as the continuous map L .

By Theorem 3 we have that the linear transformation (40) has dense image in $T_{\mathcal{R}F} \mathcal{B}_{nor}(U)$. This implies that for every F the linear map L_F is invertible. By Corollary 2.3 we have that $\mathcal{R}: \Omega_{n,p} \rightarrow \Omega_{n,p}$ is a homeomorphism. We conclude that L is invertible. It remains to show that its inverse is continuous. Since

$$E^1 = \{(F, [v]_F): F \in \Omega_{n,p} \text{ and } |[v]_F| = 1\}$$

is compact, L is invertible, and the function

$$\psi: E^1 \rightarrow \mathbb{R}^+$$

defined by $\psi(F, [v]_F) = |L(F, [v]_F)|$ is continuous, we have that

$$(41) \quad C = \min_{(F, [v]_F) \in E^1} \psi(F, [v]_F) > 0.$$

So suppose $\lim_k (F_k, [v_k]_{F_k}) = (F, [v]_F)$ and

$$L^{-1}(F_k, [v_k]_{F_k}) = (\mathcal{R}^{-1}F_k, [w_k]_{\mathcal{R}^{-1}F_k})$$

Then $\lim_k \mathcal{R}^{-1}F_k = \mathcal{R}^{-1}F$ and by (41) we have $\sup_k |[w_k]_{\mathcal{R}^{-1}F_k}| \leq \hat{C}$ for some constant \hat{C} . Taking a subsequence we can assume that $\lim_k [w_k]_{\mathcal{R}^{-1}F_k} = [\tilde{w}]_{\mathcal{R}^{-1}F}$. Since L is continuous

$$(F, [v]_F) = \lim_k L(\mathcal{R}^{-1}F_k, [w_k]_{\mathcal{R}^{-1}F_k}) = (F, L_F[\tilde{w}]_{\mathcal{R}^{-1}F}).$$

From the injectivity of L we conclude that $[\tilde{w}]_{\mathcal{R}^{-1}F} = L_F^{-1}[v]_F$. So L^{-1} is continuous. \square

Proposition 5.4. *Suppose that for every $F \in \Omega_{n,p}$ we have*

$$(42) \quad \mathfrak{B}_+(F) \subset E_F^h.$$

Then the cocycle L is uniformly expanding, that is, there is $C > 0$ and $\theta_2 > 1$ such that for every $v \in \mathcal{B}_{nor}(U)$ and $F \in \Omega_{n,p}$ we have

$$(43) \quad d(D\mathcal{R}_F^i \cdot v, E_{\mathcal{R}^i F}^h) \geq C\theta_2^i d(v, E_F^h).$$

Proof. Indeed, suppose that $[v] \in T_F \mathcal{B}_{nor}/E_F^h$ satisfies

$$\sup_i |L_F^i \cdot [v]| < \infty.$$

By Proposition 5.2, it is enough to show that $[v] = 0$, that is, $v \in E_F^h$. Firstly note that $D\mathcal{R}_F^i \cdot v = u_i + w_i$, where $\sup_i |u_i| = C < \infty$ and $w_i \in E_{\mathcal{R}^i F}^h$. Note that

$$D\mathcal{R}_{\mathcal{R}^i F} \cdot (u_i + w_i) = u_{i+1} + w_{i+1},$$

so

$$w_{i+1} = D\mathcal{R}_{\mathcal{R}^i F} \cdot u_i - u_{i+1} + D\mathcal{R}_{\mathcal{R}^i F} \cdot w_i.$$

So

$$w_{i+j} = D\mathcal{R}_{\mathcal{R}^i F}^j \cdot u_i - u_{i+j} + D\mathcal{R}_{\mathcal{R}^i F}^j \cdot w_i,$$

in particular

$$|w_{i+j}| \leq C(1 + K\theta^{-j}) + K\theta^{-j}|w_i|,$$

where K and $\theta > 1$ are as in Proposition 4.5. This implies that $\sup_i |w_i| < \infty$ and consequently

$$\sup_i |D\mathcal{R}_F^i \cdot v| < \infty.$$

By (37) we have that $v \in E_F^h$. So L is uniformly expanding. \square

Let $C > 0$ and $\theta > 1$ be as in (43). Choose $j_0 > 0$ such that

$$C\theta^{j_0} > 1.$$

If $\epsilon > 0$ is small enough we have that

$$\tilde{\theta} = Ce^{-\epsilon}\theta^{j_0} > 1.$$

Denote

$$\tilde{C} = \sup_{F \in \Omega_{n,p}} |D\mathcal{R}_F^{j_0}|.$$

Define the cone $C_F^u(K)$ as the set of all $v \in T\mathcal{B}_{nor}(U)$ that can be written as $v = u + w$, where

- A. $|u| \leq e^\epsilon d(v, E_F^h)$,
- B. $w \in E_F^h$ and
- C. $|w| \leq K|u|$.

Note that

$$(44) \quad \bigcup_{K>0} C_F^u(K) = (T\mathcal{B}_{nor}(U) \setminus E_F^h) \cup \{0\}.$$

Our goal is to show that if (43) holds then there is $K > 0$ such that

$$F \in \Omega_{n,p} \mapsto C_F^u(K)$$

is a field of unstable \mathcal{R} -invariant cones on $\Omega_{n,p}$.

Proposition 5.5. *Assume that (4.3) holds. Then for $\epsilon > 0$ small enough the following holds. Let $F \in \Omega_{n,p}$. If $v_0 = u_0 + w_0$, with*

$$0 < |u_0| \leq e^\epsilon d(v_0, E_F^h) \text{ and } w_0 \in E_F^h.$$

then for every $w_1 \in E_{\mathcal{R}^{j_0} F}^h$ and u_1 satisfying $D\mathcal{R}_F^{j_0} \cdot v_0 = u_1 + w_1$ we have

$$(45) \quad \frac{|w_1|}{|u_1|} \leq \tilde{C}\tilde{\theta}^{-1} + 1 + \tilde{\theta}^{-2} \frac{|w_0|}{|u_0|}.$$

Proof. Let $v_1 = D\mathcal{R}_F^{j_0} \cdot v_0$. In particular

$$\frac{|u_1|}{|u_0|} \geq e^{-\epsilon} \frac{d(D\mathcal{R}_F^{j_0} \cdot v_0, E_{\mathcal{R}^{j_0} F}^h)}{d(v_0, E_F^h)} \geq C e^{-\epsilon} \theta^{j_0} = \tilde{\theta} > 1.$$

Then

$$D\mathcal{R}_F^{j_0} v_0 = D\mathcal{R}_F^{j_0} u_0 + D\mathcal{R}_F^{j_0} w_0 = u_1 + w_1.$$

So

$$D\mathcal{R}_F^{j_0} \frac{u_0}{|u_1|} + D\mathcal{R}_F^{j_0} \frac{w_0}{|u_1|} = \frac{u_1}{|u_1|} + \frac{w_1}{|u_1|}$$

and

$$(46) \quad \begin{aligned} \frac{|w_1|}{|u_1|} &\leq |D\mathcal{R}_F^{j_0}| \frac{|u_0|}{|u_1|} + 1 + |D\mathcal{R}_F^{j_0} \frac{w_0}{|u_1|}| \\ &\leq \tilde{C}\tilde{\theta}^{-1} + 1 + C\theta^{-j_0} \frac{|w_0|}{|u_1|} \\ &\leq \tilde{C}\tilde{\theta}^{-1} + 1 + \tilde{\theta}^{-1} C\theta^{-j_0} \frac{|w_0|}{|u_0|} \\ &\leq \tilde{C}\tilde{\theta}^{-1} + 1 + \tilde{\theta}^{-2} \frac{|w_0|}{|u_0|}. \end{aligned}$$

□

Corollary 5.6 (Invariant Cones). *Assume that (4.3) holds. If $v_0 \in C_F^u(K_0)$ then $v_1 = D\mathcal{R}_F^{j_0} \cdot v_0 \in C_{\mathcal{R}^{j_0} F}^u(K_1)$, where*

$$K_1 = \tilde{C}\tilde{\theta}^{-1} + 1 + \tilde{\theta}^{-2} K_0.$$

Proof. We can assume that $v_0 \neq 0$. Since $v_0 \in C_F^u(K_0)$ there exist $w_0 \in E_F^h$ and u_0 such that $v_0 = u_0 + w_0$ and

$$0 < |u_0| \leq e^\epsilon d(v_0, E_F^h) \text{ and } |w_0| \leq K_0 |u_0|.$$

Moreover there exist $w_1 \in E_{\mathcal{R}^{j_0} F}^h$ and u_1 satisfying $v_1 = u_1 + w_1$, with

$$|u_1| \leq e^\epsilon d(v_1, E_{\mathcal{R}^{j_0} F}^h).$$

By Proposition 5.5 we have that $|w_1| \leq K_1 |u_1|$, so $v_1 \in C_{\mathcal{R}^{j_0} F}^u(K_1)$. □

To simplify the notation, we will replace the operator \mathcal{R} by its iteration \mathcal{R}^{j_0} . The following two corollaries are an immediate consequence of Corollary 5.6.

Corollary 5.7 (Forward Invariant Cones). *Assume that (4.3) holds. If*

$$K \geq \frac{\tilde{C}\tilde{\theta}^{-1} + 1}{1 - \tilde{\theta}^{-2}}.$$

then for every $F \in \Omega_{n,p}$

$$(47) \quad D\mathcal{R}_F C_F^u(K) \subset C_{\mathcal{R}_F}^u(K).$$

Corollary 5.8 (Absorbing Cones). *Assume that (43) holds. For each*

$$K_0 > \frac{\tilde{C}\tilde{\theta}^{-1} + 1}{1 - \tilde{\theta}^{-2}}$$

the following holds: for every $K > 0$ there exists i such that for all $F \in \Omega_{n,p}$

$$(48) \quad D\mathcal{R}_F^i C_F^u(K) \subset C_{\mathcal{R}^i F}^u(K_0).$$

Corollary 5.9 (Unstable Cones). *Assume that (43) holds. For each $K_0 > 0$ there exists $C > 0$ such that for all $F \in \Omega_{n,p}$, $v \in C_F^u(K_0)$ and $i \geq 0$*

$$(49) \quad |D\mathcal{R}_F^i v| \geq C\theta^i |v|.$$

Proof. If $v \in C_F^u(K_0)$ then $v = u + w$, with $w \in E_F^h$,

$$|u| \leq e^\epsilon d(v, E_F^h)$$

and

$$|w| \leq K_0 |u|.$$

So

$$|v| \leq |u| + |w| \leq (1 + K_0)e^\epsilon d(v, E_F^h).$$

By (43) we have

$$|D\mathcal{R}_F^i \cdot v| \geq d(D\mathcal{R}_F^i \cdot v, E_{\mathcal{R}^i F}^h) \geq C\theta^i d(v, E_F^h) \geq \frac{C}{(1 + K_0)e^\epsilon} \theta^i |v|.$$

□

Now fix

$$K_0 > \frac{\tilde{C}\tilde{\theta}^{-1} + 1}{1 - \tilde{\theta}^{-2}}.$$

Choose $i > 0$ such that

$$\theta_1 = \frac{C}{(1 + K_0)e^\epsilon} \theta^i > 1.$$

Replace (once again) the operator \mathcal{R} by its iteration \mathcal{R}^i .

Corollary 5.10 (Unstable Invariant Cones near $\Omega_{n,p}$). *Assume that (43) holds. For each*

$$(50) \quad K_0 > \frac{\tilde{C}\tilde{\theta}^{-1} + 1}{1 - \tilde{\theta}^{-2}}.$$

and $\hat{\theta} \in (1, \theta_1)$ there exists $\delta > 0$ such that if

$$\text{dist}(F, G_0) < \delta$$

for some $G_0 \in \Omega_{n,p}$ then

$$D\mathcal{R}_F C_{G_0}^u(K_0) \subset C_{\mathcal{R}G_0}^u(K_0)$$

and

$$(51) \quad |D\mathcal{R}_F \cdot v| \geq \hat{\theta} |v|.$$

for every $v \in C_{G_0}^u(K_0)$.

Proof. Define $K_1 = \tilde{C}\tilde{\theta}^{-1} + 1 + \tilde{\theta}^{-2}K_0$. Then

$$\frac{\tilde{C}\tilde{\theta}^{-1} + 1}{1 - \tilde{\theta}^{-2}} < K_1 < K_0.$$

Choose $\gamma \in (0, \epsilon)$ small enough such that

$$K_1 e^\gamma < K_0.$$

Let $v \in C_{G_0}^u(K_0)$. Then there exist $w_0 \in E_{G_0}^h$ and u_0 such that $v = u_0 + w_0$ and

$$|u_0| \leq e^\epsilon d(v, E_{G_0}^h) \text{ and } |w_0| \leq K_0 |u_0|.$$

Moreover there exist $w_1 \in E_{\mathcal{R}G_0}^h$ and u_1 satisfying

$$|u_1| \leq e^{\gamma/3} d(D\mathcal{R}_{G_0} \cdot v, E_{\mathcal{R}G_0}^h)$$

and $D\mathcal{R}_{G_0} \cdot v = u_1 + w_1$. By Proposition 5.5

$$|w_1| \leq K_1 |u_1|.$$

Then

$$(52) \quad D\mathcal{R}_F \cdot v = u_1 + (D\mathcal{R}_{G_0} - D\mathcal{R}_F) \cdot v + w_1.$$

Note that

$$\begin{aligned} & d((D\mathcal{R}_{G_0} - D\mathcal{R}_F) \cdot v, E_{\mathcal{R}G_0}^h) \\ & \leq |(D\mathcal{R}_{G_0} - D\mathcal{R}_F) \cdot v| \\ & \leq |D\mathcal{R}_{G_0} - D\mathcal{R}_F| e^\epsilon (1 + K_0) d(v, E_{G_0}^h) \\ (53) \quad & \leq |D\mathcal{R}_{G_0} - D\mathcal{R}_F| \frac{e^\epsilon (1 + K_0)}{\theta} d(D\mathcal{R}_{G_0} \cdot v, E_{\mathcal{R}G_0}^h) \end{aligned}$$

Let $\delta_1 > 0$ be such that $|F - G_0| < \delta_1$ implies

$$1 - |D\mathcal{R}_{G_0} - D\mathcal{R}_F| \frac{e^\epsilon (1 + K_0)}{\theta} \geq e^{-\gamma/3},$$

$$e^{\gamma/3} + |D\mathcal{R}_{G_0} - D\mathcal{R}_F| \frac{e^\epsilon (1 + K_0)}{\theta} \leq e^{2\gamma/3},$$

and

$$\tilde{\theta} = \theta_1 - |D\mathcal{R}_{G_0} - D\mathcal{R}_F| > \hat{\theta} > 1.$$

Then

$$\begin{aligned} & d(D\mathcal{R}_F \cdot v, E_{\mathcal{R}G_0}^h) \\ & \geq d(D\mathcal{R}_{G_0} \cdot v, E_{\mathcal{R}G_0}^h) - d((D\mathcal{R}_{G_0} - D\mathcal{R}_F) \cdot v, E_{\mathcal{R}G_0}^h) \\ (54) \quad & \geq e^{-\gamma/3} d(D\mathcal{R}_{G_0} \cdot v, E_{\mathcal{R}G_0}^h) \end{aligned}$$

so

$$\begin{aligned} |u_1 + (D\mathcal{R}_{G_0} - D\mathcal{R}_F) \cdot v| & \leq e^{\gamma/3} d(D\mathcal{R}_{G_0} \cdot v, E_{\mathcal{R}G_0}^h) + |(D\mathcal{R}_{G_0} - D\mathcal{R}_F) \cdot v| \\ & \leq e^{2\gamma/3} d(D\mathcal{R}_{G_0} \cdot v, E_{\mathcal{R}G_0}^h) \\ & \leq e^\gamma d(D\mathcal{R}_F \cdot v, E_{\mathcal{R}G_0}^h) \\ (55) \quad & \leq e^\epsilon d(D\mathcal{R}_F \cdot v, E_{\mathcal{R}G_0}^h), \end{aligned}$$

and moreover

$$\begin{aligned}
 |u_1 + (D\mathcal{R}_{G_0} - D\mathcal{R}_F) \cdot v| &\geq |u_1| - |(D\mathcal{R}_{G_0} - D\mathcal{R}_F) \cdot v| \\
 &\geq d(D\mathcal{R}_{G_0} \cdot v, E_{\mathcal{R}_{G_0}}^h) - |(D\mathcal{R}_{G_0} - D\mathcal{R}_F) \cdot v| \\
 (56) \qquad \qquad \qquad &\geq e^{-\gamma/3} d(D\mathcal{R}_{G_0} \cdot v, E_{\mathcal{R}_{G_0}}^h).
 \end{aligned}$$

Finally

$$\begin{aligned}
 |w_1| &\leq K_1 |u_1| \\
 &\leq K_1 e^{\gamma/3} d(D\mathcal{R}_{G_0} \cdot v, E_{\mathcal{R}_{G_0}}^h) \\
 &\leq K_1 e^{2\gamma/3} |u_1 + (D\mathcal{R}_{G_0} - D\mathcal{R}_F) \cdot v|. \\
 (57) \qquad \qquad \qquad &\leq K_0 |u_1 + (D\mathcal{R}_{G_0} - D\mathcal{R}_F) \cdot v|.
 \end{aligned}$$

So (52), (55) and (57) implies that $D\mathcal{R}_F \cdot v \in C_{\mathcal{R}_{G_0}}^u(K_0)$. Furthermore

$$\begin{aligned}
 |D\mathcal{R}_F \cdot v| &\geq |D\mathcal{R}_G \cdot v| - |(D\mathcal{R}_{G_0} - D\mathcal{R}_F) \cdot v| \\
 &\geq \theta_1 |v| - |D\mathcal{R}_{G_0} - D\mathcal{R}_F| |v| \\
 (58) \qquad \qquad \qquad &\geq \hat{\theta} |v|.
 \end{aligned}$$

□

Proof of Proposition 5.1. Let K_0 be as in Corollary 5.10. We claim that every cone $C_F^u(K_0)$, with $F \in \Omega_{n,p}$, contains a subspace S_F of dimension n . Indeed, since E_G^h , $G \in \Omega_{n,p}$, has finite codimension n there is a subspace $E_G \subset T\mathcal{B}_{nor}(U)$ of dimension n such that

$$E_G \oplus E_G^h = T\mathcal{B}_{nor}(U).$$

Since $\Omega_{n,p}$ is a Cantor set and $G \mapsto E_G^h$ is a continuous distribution, it is easy to see that we can find a finite covering $\{O_j\}_j$ by compact subsets of $\Omega_{n,p}$ and subspaces E_j with dimension n such that

$$E_j \oplus E_G^h = T\mathcal{B}_{nor}(U)$$

for every $G \in O_j$. By (44), Proposition 5.5 and Corollary 5.8 there exists i_0 such that

$$D\mathcal{R}_G^{i_0} E_j \subset C_{\mathcal{R}^{i_0} G}^u(K_0).$$

for every $G \in O_j$. Moreover \mathcal{R} is invertible on $\Omega_{n,p}$, so we can choose G such that $\mathcal{R}^{i_0} G = F$. Since $D\mathcal{R}_G$ is injective for every $G \in \Omega_{n,p}$ we conclude that $S_F = D\mathcal{R}_G^{i_0} E_j$ is a subspace of dimension n in $C_F^u(K_0)$. This concludes the proof of the claim. Note that

$$S_F \oplus E_F^h = T\mathcal{B}_{nor}(U).$$

Let $G \in \Omega_{n,p}$. Since \mathcal{R} is invertible on $\Omega_{n,p}$ there is a unique sequence $G_i \in \Omega_{n,p}$ such that $\mathcal{R} G_{i+1} = G_i$ and $G_0 = G$. Let S'_i be an arbitrary subspace of dimension n contained in $C_{G_i}^u(K_0)$, Then $D\mathcal{R}_{G_i}^i(S'_i)$ is a subspace of dimension n contained in $C_G^u(K_0)$. Since

$$(59) \qquad \qquad \qquad C_G^u(K_0) \cap E_G^h = \{0\}$$

we have that there is a linear function

$$\mathcal{H}_i: S_G \rightarrow E_G^h$$

such that $\{v + \mathcal{H}_i(v), v \in S_G\} = D\mathcal{R}_{G_i}^i(S'_i)$. Since $v + \mathcal{H}_i(v) \in C_G^u(K_0)$ we have $v + \mathcal{H}_i(v) = u_1 + w_1$, with $w_1 \in E_G^h$ and

$$|u_1| \leq e^\epsilon d(v + \mathcal{H}_i(v), E_G^h) = e^\epsilon d(v, E_G^h) < e^\epsilon |v|.$$

and $|w_1| \leq K_0|u_1|$. In particular

$$|\mathcal{H}_i(v)| = |u_1 + w_1 - v| \leq (1 + e^\epsilon(1 + K_0))|v|,$$

So the family of functions \mathcal{H}_i is an equicontinuous family of functions. By the strong compactness of the operator \mathcal{R} and Arzela-Ascoli Theorem there exists a subsequence that converges to a bounded linear function $\mathcal{H}^G: S_G \rightarrow E_G^h$ satisfying

$$\{v + \mathcal{H}^G(v), v \in S_G\} \subset \bigcap_{i=0}^{\infty} \overline{D\mathcal{R}_{G_i}^i C_{G_i}^u(K_0)} \subset C_G^u(K_0).$$

Due (59) and the contraction in the horizontal directions we have that there is only one possible accumulation point \mathcal{H}^G for sequences as $(\mathcal{H}_i)_i$. Let

$$E_G^u = \{v + \mathcal{H}^G(v), v \in S_G\}.$$

Then we can easily conclude that $D\mathcal{R}_G(E_G^u) = E_{\mathcal{R}G}^u$. Then $G \mapsto E_G^u$ is the unstable direction of \mathcal{R} . \square

6. INDUCED EXPANDING MAPS.

Let $F \in \Omega_{n,p}$. We are going to define a real induced map $G_{\mathbb{R}}: D \rightarrow \mathbb{R}$ for F whose domain D is the union of intervals R_{-i}^k , $k \geq 0$ and $0 < i < n_r^k$, $r \in C(F)$, satisfying

$$R_{-i}^k \subset \bigcup_{q \in C(F)} Q_0^{k-1}.$$

If $R_{-i}^k \subset Q_0^{k-1}$ and $s \in C(F)$ is the successor of q at the $k-1$ level we define $G_{\mathbb{R}}(x) = F^{n_s^{k-1}}(x)$ for every $x \in R_{-i}^k$. Note that

$$G_{\mathbb{R}}: R_{-i}^k \rightarrow R_{-i+n_s^{k-1}}^k$$

is a diffeomorphism. Due the real bounds there exists ϵ_0 such that

$$(60) \quad 0 < \epsilon_0 < \inf_{r \in C(F), k} \frac{2 \text{dist}(P(F), \partial R_0^k)}{|R_0^k|}.$$

We will now define a complex-analytic extension G of $G_{\mathbb{R}}$ that is a conformal iterated dynamical system. Suppose that $R_{-i}^k \subset Q_0^{k-1}$. Let \mathcal{R}_0^k be the ball $B(r, d_r^k)$, where

$$(61) \quad d_r^k = (1 - \frac{\epsilon_0}{16}) \frac{|R_0^k|}{2}.$$

Since F belongs to the Epstein class, there exists a simply connected domain \mathcal{R}_{-i}^k such that $\mathcal{R}_{-i}^k \cap \mathbb{R} \subset R_{-i}^k$ and \mathcal{R}_{-i}^k is contained in the ball whose diameter is $R_{-i}^k \cap \mathbb{R}$ and moreover

$$F^i: \mathcal{R}_{-i}^k \rightarrow \mathcal{R}_0^k$$

is univalent. Due the real bounds, we can reduce ϵ_0 if necessary in such way that

$$\mathcal{R}_{-i}^k \subset Q_0^{k-1}$$

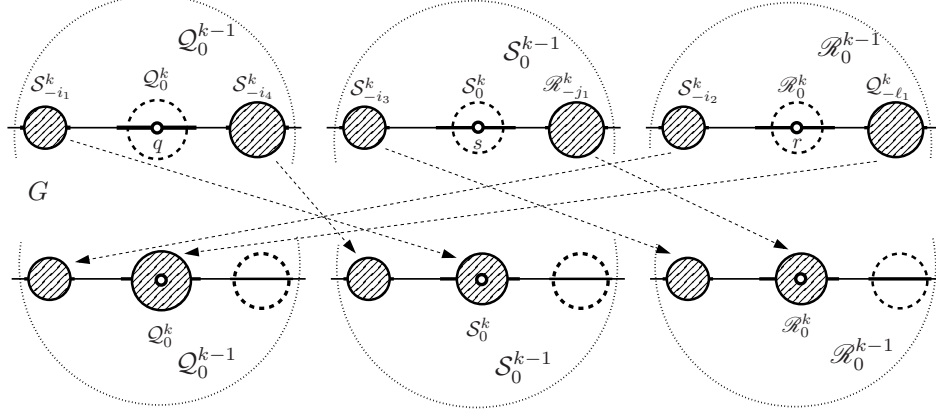


FIGURE 2. How G acts on the domains $\mathcal{R}_{-i}^k \subset \cup_{q \in C(F)} \mathcal{Q}_0^{k-1}$ if the combinatorics of the k -th renormalization is the same as the combinatorics of the renormalization $R(F)$ in Fig. 1. At level $k-1$ we have that s is the sucessor of q , r is the sucessor of s and q is the sucessor of r . At level k we have that r is the sucessor of q , s is the sucessor of r and q is the sucessor of s . Moreover $\ell_1, j_1 > 0$ and $0 < i_1 < i_2 < i_3 < i_4$.

for every $R_{-i}^k \subset Q_0^{k-1}$ and

$$\inf_k \inf_{\substack{\{q,r\} \subset C(F) \\ R_{-i}^k \subset Q_0^{k-1}}} \text{dist}(\mathcal{R}_{-i}^k, \partial Q_0^{k-1}) > 0$$

We define G on

$$\mathcal{D} = \bigcup_k \bigcup_{r, q \in C(F)} \bigcup_{R_{-i}^k \subset Q_0^{k-1}} \mathcal{R}_{-i}^k$$

as $G(z) = F^{n_s^{k-1}}(z)$ for every $z \in \mathcal{R}_{-i}^k$, where $R_{-i}^k \subset Q_0^{k-1}$ and $s \in C(F)$ is the sucessor of q at level $k-1$. Note that $P(F) \setminus C(F) \subset \mathcal{D}$ and

$$G(P(F) \setminus C(F)) = P(F).$$

Lemma 6.1 (Markovian property of the induced map). *Let $r_j \in C(F)$, $m_i \in \mathbb{N}$ and $0 \leq i_j < n_{r_j}^{m_i}$, $j \leq \ell$ be such that*

- A. *either we have that $m_{j+1} = m_j$, $i_{j+1} < i_j$, $r_{j+1} = r_j = r$ for some $r \in C(F)$ and moreover*

$$R_{-i_j}^{m_j}, R_{-i_{j+1}}^{m_j} \subset \bigcup_{q \in C(F)} Q_0^{m_j-1}.$$

and

$$R_{-i}^{m_j} \not\subset \bigcup_{q \in C(F)} Q_0^{m_j-1}$$

for every i satisfying $i_{j+1} < i < i_j$. In particular

$$G_{\mathbb{R}}: R_{-i_j}^{m_j} \mapsto R_{-i_{j+1}}^{m_{j+1}}.$$

is a diffeomorphism.

B. or

$$m_{j+1} > m_j,$$

with

$$R_{-i_j}^{m_j} \subset \bigcup_{q \in C(F)} Q_0^{m_j-1},$$

and

$$R_{-i}^{m_j} \not\subset \bigcup_{q \in C(F)} Q_0^{m_j-1}$$

for every i satisfying $0 < i < i_j$. Here $r = r_j$. In particular

$$G: R_{-i_j}^{m_j} \mapsto R_0^{m_j}.$$

is a diffeomorphism. Moreover $i_{j+1} > 0$ and

$$S_{-i_{j+1}}^{m_{j+1}} \subset R_0^{m_{j+1}-1},$$

where $s = r_{j+1}$. In particular

$$G_{\mathbb{R}}: R_{-i_j}^{m_j} \mapsto R_0^{m_j}.$$

is a diffeomorphism and

$$S_{-i_{j+1}}^{m_{j+1}} \subset R_0^{m_j} = G_{\mathbb{R}}(R_{-i_j}^{m_j}).$$

Then there exists a unique interval W such that

$$G_{\mathbb{R}}^{\ell}: W \rightarrow R_{-i_{\ell}}^{m_{\ell}}$$

is a diffeomorphism and W is the set of points z such that for every $j \leq \ell$ we have $G_{\mathbb{R}}^j(z) \in Q_{-i_j}^{m_j}$, where $q = r_j$. Moreover $W = R_{-i}^{m_{\ell}}$, for some i , where $r = r_{\ell}$.

Proof. If $\ell = 0$, there is nothing to prove, since $W = R_{-i_0}^{m_0}$, with $r = r_0$. Suppose by induction on ℓ that Lemma 6.1 holds for ℓ . Let $r_j \in C(F)$, $m_i \in \mathbb{N}$ and $0 < i_j < n_{r_j}^{m_i}$, $j \leq \ell + 1$ be as in the statement of the lemma. By the induction assumption there exists b such that

$$G_{\mathbb{R}}^{\ell}: R_{-b}^{m_{\ell+1}} \rightarrow R_{-i_{\ell+1}}^{m_{\ell+1}}$$

is a diffeomorphism and for every $j \leq \ell$ we have $G_{\mathbb{R}}^j R_{-b}^{m_{\ell+1}} \subset Q_{-i_{j+1}}^{m_{j+1}}$, where $q = r_{j+1}$. In particular $R_{-b}^{m_{\ell+1}} \subset S_{-i_1}^{m_1}$, with $s = r_1$. There are two cases. If $m_0 = m_1$ then $S_{-i_0}^{m_0} = S_{-i_0}^{m_1}$, $i_0 > i_1$, and

$$G_{\mathbb{R}}: S_{-i_0}^{m_1} \rightarrow S_{-i_1}^{m_1}$$

is a diffeomorphism, and $W = R_{-(b+i_0-i_1)}^{m_{\ell}}$ is the unique interval $W \subset S_{-i_0}^{m_1}$ such that $G_{\mathbb{R}}(W) = R_{-b}^{m_{\ell}}$. If $m_1 > m_0$ then $S_{-i_1}^{m_1} \subset Q_0^{m_0}$, with $q = m_0$, and

$$G: Q_{-i_0}^{m_0} \rightarrow Q_0^{m_0}$$

is a diffeomorphism. Then $W = R_{-(b+i_0)}^{m_{\ell}}$ is the unique interval $W \subset Q_{-i_0}^{m_0}$ such that $G(W) = R_{-b}^{m_{\ell}}$. \square

The next proposition says that the postcritical set $P(F)$ of F is the maximal invariant set of the induced map G .

Proposition 6.2. *Given $(z, j) \in \mathcal{D}$ we have that (z, j) belongs to $\mathcal{D} \setminus P(F)$ if and only if there exists $k_0 \geq 0$ such that $G^k(z, j) \in \mathcal{D}$ for every $k < k_0$ and $G^{k_0}(z, j) \notin \mathcal{D}$.*

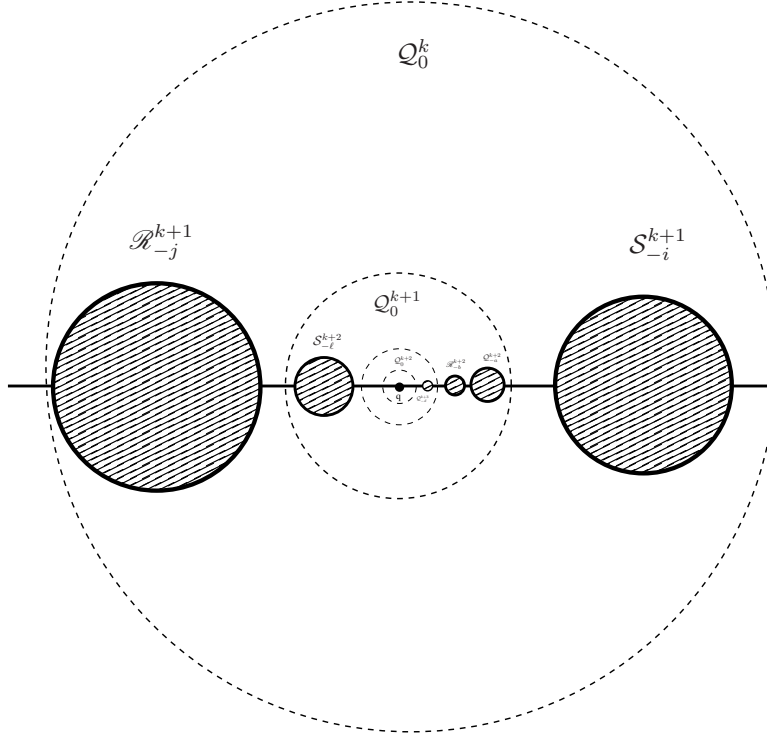


FIGURE 3. The domain \mathcal{D} of G close to a critical point q (the point in the center). It contains infinitely many topological disks accumulating on the critical point q .

Proof. Let $r_j \in C(F)$, $m_i \in \mathbb{N}$ and $0 < i_j < n_{r_j}^{m_i}$ such that either

$$m_{j+1} > m_j$$

and

$$R_{-i_{j+1}}^{m_{j+1}} \subset Q_0^{m_j}.$$

where $r = r_{j+1}$ and $q = r_j$, or $m_{j+1} = m_j$ and $i_{j+1} = i_j - 1$. We claim that there exists a unique $z \in \mathbb{C}_n$ such that

$$(62) \quad G^j(z) \in \mathcal{R}_{-i_j}^{m_j}$$

for every $j \geq 0$. Indeed, for each ℓ , let D_ℓ be the set of points such that (62) holds for every $j \leq \ell$. Of course $D_{\ell+1} \subset D_\ell$. If $m_{\ell+1} = m_\ell$ then $D_{\ell+1} = D_\ell$. If $m_{\ell+1} > m_\ell$ then

$$G^{\ell+1}: D_\ell \rightarrow Q_0^{m_\ell},$$

with $q = r_\ell$ and

$$G^{\ell+1}: D_{\ell+1} \rightarrow \mathcal{R}_{-i_{\ell+1}}^{m_{\ell+1}},$$

with $r = r_{\ell+1}$, are univalent (and onto). By the definition of G

$$M = \inf_m \inf_{\mathcal{R}_{-i}^{m+1} \subset Q_0^m} \text{mod} (Q_0^m \setminus \mathcal{R}_{-i}^{m+1}) > 0,$$

so

$$\text{mod} (D_\ell \setminus D_{\ell+1}) = \text{mod} (Q_0^{m_\ell} \setminus \mathcal{R}_{-i_{\ell+1}}^{m_{\ell+1}}) \geq M,$$

in particular, since there exists infinitely many ℓ such that $m_{\ell+1} > m_\ell$ we have that

$$\lim_{\ell} \text{diam}(D_\ell) = 0$$

and

$$\cap_{\ell} D_\ell = \{z_0\}$$

for some $z_0 \in \mathcal{D}$. This completes the proof of the claim. Note that since D_ℓ are symmetric with respect to the \mathbb{R} we have that $z_0 \in \mathbb{R}$ and by (62)

$$(63) \quad G^j(z_0) \in \mathcal{R}_{-i_j}^{m_j} \cap \mathbb{R} \subset R_{-i_j}^{m_j},$$

where $r = r_j$, for every j . By Lemma 6.1 there exists b_j such that

$$z_0 \in R_{-b_j}^{m_j},$$

where $r = r_j$, for every $j \geq 0$. In particular $z_0 \in P(F)$. □

7. INDUCED PROBLEM.

Let a_i be as in (15). Define the function

$$V: \mathcal{D} \rightarrow \mathbb{C}$$

as

$$V(z) = a_i(z) = \frac{\partial}{\partial t} (F_t)^{n_s^{k-1}}(z) \Big|_{t=0}$$

for every $z \in \mathcal{R}_{-i}^k \subset \mathcal{D}$, provided $R_{-i}^k \subset Q_0^{k-1}$ and s is the successor of q at the $k-1$ level. Here $F_t = F + tv$.

Lemma 7.1. *Suppose that α is a continuous vector field in a neighbourhood of $P(F)$, such that*

A1. $\alpha(c) = 0$ for every $c \in C(F)$, and

A2. *We have*

$$(64) \quad V(z) = \alpha \circ G(z) - DG(z) \cdot \alpha(z)$$

for every $z \in P(F) \setminus C(F)$.

Let $x \in P(F)$ and $\ell > 0$ such that $G^j(x) \notin C(F)$ for every $0 \leq j < \ell$. Then for each $j < \ell$ there is $r, q \in C(F)$, with $b_j > 0$ such that $G^j(x) \in R_{-b_j}^{k_j} \subset Q_0^{k_j-1}$.

Define $i_j = n_s^{k_j-1}$, where $s \in C(F)$ is the successor of q at level $k-1$. Note that the critical points q, s, r may depend on x and j . Let

$$m = \sum_{j=0}^{\ell-1} i_j.$$

Then

B1. For every $z \in \mathbb{C}$ close enough to x we have that $G^\ell(z)$ is well defined and $G^\ell(z) = F^m(z)$.

B2. For every $z \in P(F)$ close enough to x we have that $\alpha(G^\ell(z))$ is well defined and

$$\alpha(z) = \frac{\alpha(G^\ell(z))}{DG^\ell(z)} - \sum_{a=1}^m \frac{v(F^{a-1}(z))}{DF^a(z)}.$$

B3. In particular for every $z \in P(F)$ close enough to x such that $G^\ell(x) \in C(F)$ we have

$$\alpha(x) = - \sum_{a=1}^m \frac{v(F^{a-1}(x))}{DF^a(x)}.$$

Proof. We let to the reader to show that $G^\ell(z) = F^m(z)$ for z close enough to x . By (64) we get

$$\alpha(x) = \frac{\alpha(G^\ell(z))}{DG^\ell(z)} - \sum_{j=1}^{\ell} \frac{V(G^{j-1}(x))}{DG^j(z)}.$$

So

$$\begin{aligned} \sum_{j=1}^{\ell} \frac{V(G^{j-1}(x))}{DG^j(z)} &= \sum_{j=1}^{\ell} \frac{(\partial_t(F_t)^{i_j})(F^{i_0+i_1+\dots+i_{j-1}}(z))}{DF^{i_0+i_1+\dots+i_j}(z)} \\ &= \sum_{j=1}^{\ell} \sum_{b=0}^{i_j-1} \frac{DF^{i_j-b-1}(F^{b+1}(F^{i_0+i_1+\dots+i_{j-1}}(z)))v(F^b(F^{i_0+i_1+\dots+i_{j-1}}(z)))}{DF^{i_0+i_1+\dots+i_j}(z)} \\ &= \sum_{j=1}^{\ell} \sum_{b=0}^{i_j-1} \frac{DF^{i_j-b-1}(F^{b+1}(F^{i_0+i_1+\dots+i_{j-1}}(z)))v(F^{i_0+i_1+\dots+i_{j-1}+b}(z))}{DF^{i_j-b-1}(F^{b+1}(F^{i_0+i_1+\dots+i_{j-1}}(z)))DF^{i_0+i_1+\dots+i_{j-1}+b+1}(z)} \\ &= \sum_{j=1}^{\ell} \sum_{b=0}^{i_j-1} \frac{v(F^{i_0+i_1+\dots+i_{j-1}+b}(z))}{DF^{i_0+i_1+\dots+i_{j-1}+b+1}(z)} = \sum_{a=1}^m \frac{v(F^{a-1}(z))}{DF^a(z)}. \end{aligned}$$

□

Proposition 7.2. Suppose that α is a continuous vector field in a neighbourhood of $P(F)$, such that $\alpha(r) = 0$ for every $r \in C(F)$ and

$$(65) \quad V(z) = \alpha \circ G(z) - DG(z) \cdot \alpha(z).$$

for every $z \in P(F) \setminus C(F)$. Then

$$(66) \quad v(z) = \alpha \circ F(z) - DF(z) \cdot \alpha(z)$$

for every $z \in P(F)$.

Proof. For each R_{-m}^k , with $r \in C(F)$ and $0 < m < n_r^k$, there exists a unique $r_{-m}^k \in R_{-m}^k$ such that

$$F^m(r_{-m}^k) = r.$$

The set

$$\Gamma = \{r_{-m}^k\}_{r \in C(F), 0 < m < n_r^k} \subset P(F)$$

is dense on $P(F)$ and

$$F(\Gamma) = \Gamma \cup C(F).$$

We claim that (66) holds for every $z \in \Gamma$. Indeed, given $r_{-m}^k \in \Gamma$, there exists $\ell > 0$ such that $G^\ell(r_{-m}^k) = 0$. Moreover by Lemma 7.1 we have that $G^\ell = F^m$ in a neighbourhood of r_{-m}^k and

$$(67) \quad \alpha(r_{-m}^k) = - \sum_{a=1}^m \frac{v(F^{a-1}(r_{-m}^k))}{DF^a(r_{-m}^k)}.$$

Suppose that $m = 1$. Then $\ell = 1$, $G = F$ in a neighbourhood of r_{-1}^k , $V(r_{-1}^k) = v(r_{-1}^k)$ and $G(r_{-1}^k) \in C(F)$. By (65) it follows that

$$v(r_{-1}^k) = \alpha \circ G(r_{-1}^k) - DG(r_{-1}^k) \cdot \alpha(r_{-1}^k) = \alpha \circ F(r_{-1}^k) - DF(r_{-1}^k) \cdot \alpha(r_{-1}^k).$$

If $m > 1$ then $F(r_{-m}^k) = r_{-(m-1)}^k \in \Gamma$, so by (67) we have

$$\begin{aligned} & \alpha(F(r_{-m}^k)) - DF(r_{-m}^k)\alpha(r_{-m}^k) \\ &= - \sum_{a=1}^{m-1} \frac{v(F^{a-1}(r_{-(m-1)}^k))}{DF^a(r_{-(m-1)}^k)} + DF(r_{-m}^k) \sum_{b=1}^m \frac{v(F^{b-1}(r_{-m}^k))}{DF^b(r_{-m}^k)} \\ &= - \sum_{a=1}^{m-1} \frac{v(F^{a-1}(r_{-(m-1)}^k))}{DF^a(r_{-(m-1)}^k)} + \sum_{b=1}^m \frac{v(F^{b-1}(r_{-m}^k))}{DF^{b-1}(r_{-(m-1)}^k)} \\ &= - \sum_{a=1}^{m-1} \frac{v(F^{a-1}(r_{-(m-1)}^k))}{DF^a(r_{-(m-1)}^k)} + v(r_{-m}^k) + \sum_{b=2}^m \frac{v(F^{b-2}(r_{-(m-1)}^k))}{DF^{b-1}(r_{-(m-1)}^k)} \\ &= - \sum_{a=1}^{m-1} \frac{v(F^{a-1}(r_{-(m-1)}^k))}{DF^a(r_{-(m-1)}^k)} + v(r_{-m}^k) + \sum_{a=1}^{m-1} \frac{v(F^{a-1}(r_{-(m-1)}^k))}{DF^a(r_{-(m-1)}^k)} \\ &= v(r_{-m}^k). \end{aligned}$$

So (66) holds for every $z \in \Gamma$. Since v , α and F are continuous in a neighbourhood of $P(F)$ and Γ is dense in $P(F)$, it follows that (66) holds for every $z \in P(F)$. \square

Corollary 7.3 (Induced problem). *Let $F \in \Omega_{n,p}$ and $v \in \mathfrak{B}_+(F)$. If there exists a quasiconformal vector field α , defined in a neighbourhood of $P(F)$, such that $\alpha(r) = 0$ for every $r \in C(F)$ and*

$$(68) \quad V(z) = \alpha \circ G(z) - DG(z) \cdot \alpha(z)$$

for every $z \in P(F) \setminus C(F)$, then $v \in E^h(F)$.

Proof. This is an immediate consequence of Proposition 4.1 and Proposition 7.2. \square

8. SOLVING THE INDUCED PROBLEM.

We are going to change a little bit the notation. Let P_i^k , $i = 1, \dots, n$ be the set of restrictive intervals for F associated to the renormalization $\mathcal{R}^k F$, that is

A. These intervals are pairwise disjoint, $C(F) \cap P_i^k \neq \emptyset$ and

$$C(F) \subset \cup_i P_i^k.$$

B. There are integers n_i^k such that

$$F^{n_i^k} : P_i^k \rightarrow P_{i+1 \bmod n}^k$$

is an unimodal map.

C. They have that $P_i^k = [\delta_i^k, b_i^k]$, where δ_i^k is a $\mu^{(k)}$ -periodic repelling fixed point, with

$$\mu^{(k)} = \sum_i n_i^k,$$

and $F^{n_i^k}(\delta_i^k) = F^{n_i^k}(b_i^k)$.

D. The renormalization associated to the restrictive interval P_1^k is $\mathcal{R}^k F$.

If t is small enough then $F_t = F + tv$ is close to F and δ_i^k has an analytic continuation $\delta_i^k(t)$. Denote by $\partial_t \delta_i^k$ the derivative of this continuation with respect to t at $t = 0$. Consider $\{q_i^k\} = C(F) \cap P_i^k$. Then q_{i+1}^k is the successor of q_i^k at level k . Let $j_i^k \in \{1, \dots, n\}$ be such that $q_i^k \in I_{j_i^k}$, and

$$A_i^k : \mathbb{C} \times \{j_i^k\} \rightarrow \mathbb{C} \times \{i\}$$

be the only affine transformation such that $A_i^k(\delta_i^k) = (-1, i)$ and $A_i^k(q_i^k) = (0, i)$.

Lemma 8.1. *We have $V = V_1 + V_2$, where*

$$(69) \quad V_1(z, j_i^k) = -\delta_{i+1}^k v^k \circ A_i^k(z, j_i^k),$$

and

$$(70) \quad V_2(z, j_i^k) = \frac{\partial_t \delta_{i+1}^k}{\delta_{i+1}^k} F^{n_i^k}(z, j_i^k) - DF^{n_i^k}(z, j_i^k) \cdot \frac{\partial_t \delta_i^k}{\delta_i^k}(z, j_i^k)$$

for every $(z, j_i^k) \in \mathcal{R}_{-\ell}^{k+1}$, with $R_{-\ell}^{k+1} \subset Q_0^k$, $q = q_i^k$.

Proof. Note that

$$\begin{aligned} v^k(x, i) &= \partial_t(\mathcal{R}^k(F_t))|_{t=0}(x, i) = (D\mathcal{R}_F^k \cdot v)(x, i) \\ &= -\frac{\partial_t \delta_{i+1}^k}{\delta_{i+1}^k} \cdot A_{i+1}^k \circ F^{n_i^k} \circ (A_i^k)^{-1}(x, i) \\ &\quad - \frac{1}{\delta_{i+1}^k} (a_{n_i^k} \circ (A_i^k)^{-1}(x, i) + (DF^{n_i^k}) \circ (A_i^k)^{-1}(x, i) \cdot (-\partial_t \delta_i^k x, i)), \end{aligned}$$

So if $(x, i) = A_i^k(z, j_i^k)$, with $(z, j_i^k) \in \mathcal{R}_{-\ell}^{k+1}$, with $R_{-\ell}^{k+1} \subset Q_0^k$ we have that

$$\begin{aligned} V(z, j_i^k) &= a_{n_i^k}(z, j_i^k) \\ &= -\delta_{i+1}^k v^k \circ A_i^k(z, j_i^k) + \frac{\partial_t \delta_{i+1}^k}{\delta_{i+1}^k} F^{n_i^k}(z, j_i^k) - DF^{n_i^k}(z, j_i^k) \cdot \frac{\partial_t \delta_i^k}{\delta_i^k}(z, j_i^k). \end{aligned}$$

□

Lemma 8.2. *Let $v \in \mathfrak{B}_+(F)$. There exists $C_3 > 0$ such that for every k and every i_k, i_{k+1} such that $q_{i_k}^k = q_{i_{k+1}}^{k+1}$ we have*

$$(71) \quad \left| \frac{\partial_t \delta_{i_{k+1}}^{k+1}}{\delta_{i_{k+1}}^{k+1}} - \frac{\partial_t \delta_{i_k}^k}{\delta_{i_k}^k} \right| \leq C_3$$

Proof. Let $q = q_{i_k}^k = q_{i_{k+1}}^{k+1}$ and i_j be such that $q_{i_j}^j = q$. Note that $\beta_q^{k+1} = A_i^k(\delta_{i_{k+1}}^{k+1})$ is a periodic point for $\mathcal{R}^k F$ with period $y^k = \mu^{(k+1)}/\mu^{(k)}$. Indeed

$$\beta_q^{k+1} = \left(\frac{\delta_{i_{k+1}}^{k+1}}{\delta_{i_k}^k}, i_k \right).$$

If t is small enough then there is an analytic continuation $\beta_q^{k+1}(t)$ for β_q^{k+1} , that is a periodic point for $\mathcal{R}^k F_t$. Since

$$\partial_t(\mathcal{R}^k(F_t))|_{t=0}(x, i) = (D\mathcal{R}_F^k \cdot v)(x, i) = v^k(x, i),$$

by the Implicit Function Theorem we have that

$$\partial_t(\mathcal{R}^k(F_t))^{y^k}|_{t=0}(\beta_q^{k+1}) + D(\mathcal{R}^k F)^{y^k}(\beta_q^{k+1})\partial_t \beta_q^{k+1} = \partial_t \beta_q^{k+1}.$$

So

$$\begin{aligned}
& \partial_t \beta_q^{k+1} \\
&= \frac{1}{1 - D(\mathcal{R}^k F)^{y^k}(\beta_q^{k+1})} \sum_{j=0}^{y^k-1} D(\mathcal{R}^k F)^{y^k-j-1}((\mathcal{R}^k F)^{j+1}(\beta_q^{k+1})) v^k((\mathcal{R}^k F)^j(\beta_q^{k+1})) \\
&= \sum_{\ell=1}^{\infty} \frac{-1}{D(\mathcal{R}^k F)^{y^k \ell}(\beta_q^{k+1})} \sum_{j=0}^{y^k-1} D(\mathcal{R}^k F)^{y^k-j-1}((\mathcal{R}^k F)^{j+1}(\beta_q^{k+1})) v^k((\mathcal{R}^k F)^j(\beta_q^{k+1})) \\
&= \sum_{\ell=1}^{\infty} \sum_{j=0}^{y^k-1} -\frac{v^k((\mathcal{R}^k F)^{y^k(\ell-1)+j}(\beta_q^{k+1}))}{D(\mathcal{R}^k F)^{y^k(\ell-1)+j+1}(\beta_q^{k+1})} \\
&= \sum_{a=0}^{\infty} -\frac{v^k((\mathcal{R}^k F)^a(\beta_q^{k+1}))}{D(\mathcal{R}^k F)^{a+1}(\beta_q^{k+1})}
\end{aligned}$$

Due the real bounds and $v \in \mathfrak{B}_+(F)$ there exist C_1, C_2 such that

$$\sup_k \{|D(\mathcal{R}^k F)|_{\mathcal{B}(V)}, |\beta_q^k|, \frac{1}{|\beta_q^k|}, |v^k|_{\mathcal{B}(V)}\} \leq C_1$$

and

$$1 < C_2 < \inf_{k,q} |D(\mathcal{R}^k F)^{y^k}(\beta_q^{k+1})|.$$

So

$$(72) \quad \sup_{k,q} \left| \frac{\partial_t \beta_q^{k+1}}{\beta_q^{k+1}} \right| = C_3 < \infty.$$

If i_j satisfies $q_{i_j}^j = q$ then

$$\delta_{i_{k+1}}^{k+1}(t) = \prod_{j=0}^k \frac{\delta_{i_{j+1}}^{j+1}(t)}{\delta_{i_j}^j(t)} = \prod_{j=1}^{k+1} \beta_q^j(t),$$

if we derive with respect to t at $t = 0$ we obtain

$$\partial_t \delta_{i_{k+1}}^{k+1} = \sum_{j=1}^{k+1} \partial_t \beta_q^j \prod_{\ell \neq j} \beta_q^\ell$$

and we conclude that

$$(73) \quad \frac{\partial_t \delta_{i_{k+1}}^{k+1}}{\delta_{i_{k+1}}^{k+1}} = \sum_{j=1}^{k+1} \frac{\partial_t \beta_q^j}{\beta_q^j}$$

and

$$(74) \quad \left| \frac{\partial_t \delta_{i_{k+1}}^{k+1}}{\delta_{i_{k+1}}^{k+1}} - \frac{\partial_t \delta_{i_k}^k}{\delta_{i_k}^k} \right| = \left| \frac{\partial_t \beta_q^{k+1}}{\beta_q^{k+1}} \right| \leq C_3$$

□

Lemma 8.3. *For every $(z, j_i^k) \in \mathcal{R}_{-\ell}^{k+1}$, with $R_{-\ell}^{k+1} \subset Q_0^k$, $q = q_i^k$ we have*

$$(75) \quad |V_1(z, j_i^k)| \leq |\delta_{i+1}^k| \sup_k |v^k|,$$

and

$$(76) \quad |V_2(z, j_i^k)| \leq C_3 k |\delta_{i+1}^k| + C_3 k |\delta_i^k| \sup |DG|$$

In particular

$$\lim_{w \rightarrow C(F)} V(w) = 0.$$

Proof. It follows from Lemma 8.1 and Lemma 8.2. \square

Lemma 8.4. *Let $\psi: \mathbb{R}_+^* \rightarrow \mathbb{R}$ be a C^∞ function. Define $\gamma: \mathbb{C} \setminus \{0\} \rightarrow \mathbb{C}$ as*

$$\gamma(z) = \psi(|z|)z.$$

Then

$$|\bar{\partial}\gamma(z)| = \frac{|zD\psi(|z|)|}{2}.$$

If $|D\psi(t)| \leq Ct^{-1}$ then γ can be extended as a quasiconformal vector field on \mathbb{C} such that $\gamma(0) = 0$.

Proof. If $z = x + iy$, $x, y \in \mathbb{R}$ then

$$\psi(|z|) = \psi(\sqrt{x^2 + y^2}),$$

In particular

$$\bar{\partial}(\psi(|z|)) = \frac{2xD\psi(\sqrt{x^2 + y^2})}{4\sqrt{x^2 + y^2}} + i \frac{2yD\psi(\sqrt{x^2 + y^2})}{4\sqrt{x^2 + y^2}},$$

and

$$|\bar{\partial}(\psi(|z|))| = \frac{|D\psi(|z|)|}{2}.$$

In particular

$$|\bar{\partial}(\psi(|z|)z)| = \frac{|zD\psi(|z|)|}{2}.$$

Let $\epsilon \in (0, 1)$. Note that

$$|\psi(1) - \psi(\epsilon)| = \left| \int_\epsilon^1 D\psi(t) dt \right| \leq \int_\epsilon^1 \frac{1}{t} dt = -\ln \epsilon.$$

$$|\psi(\epsilon)| \leq -\ln \epsilon + |\psi(1)|.$$

In particular

$$(77) \quad \lim_{z \rightarrow 0} z\psi(|z|) = 0,$$

so defining $\gamma(0) = 0$ we obtain a continuous extension to \mathbb{C} of γ . To show that γ is a quasiconformal vector field, note that

$$|\bar{\partial}\gamma(z)| = \frac{|zD\psi(|z|)|}{2} \leq \frac{C}{2}$$

for every $z \in \mathbb{C} \setminus \{0\}$. By [1, Lemma 3, page 53] there exists a quasiconformal vector field $\tilde{\gamma}$ on \mathbb{C} such that its distributional derivative belongs to $L^2(\mathbb{C})$, it satisfies $\bar{\partial}\tilde{\gamma}(z) = 0$ if $|z| \geq 1$ and

$$\bar{\partial}\tilde{\gamma}(z) = \bar{\partial}\gamma(z)$$

for almost every z satisfying $|z| < 1$. So $\gamma - \tilde{\gamma}$ is continuous on $\{z \in \mathbb{C}: |z| < 1\}$ and (by Weyl's Lemma) holomorphic on $\{z \in \mathbb{C}: 0 < |z| < 1\}$. By Riemann's Theorem on removable singularities we have that 0 is a removable singularity, so $\gamma - \tilde{\gamma}$ is holomorphic on $|z| < 1$, and therefore γ is quasiconformal on \mathbb{C} . \square

An illustrative example of application of Lemma 8.4 is obtained considering $\psi(x) = \log(x)$.

Proposition 8.5. *Let $v \in \mathfrak{B}_+(F)$. There exists a quasiconformal vector field $\alpha_2: \mathbb{C}_n \rightarrow \mathbb{C}$ such that*

$$(78) \quad V_2(z, j) = \alpha_2 \circ G(z, j) - DG(z, j) \cdot \alpha_2(z, j)$$

for every $(z, j) \in \partial\mathcal{D}$ and moreover $\alpha_2(0, j) = 0$ for every j .

Proof. Due the real bounds we have that

$$(79) \quad \inf_{q \in C(F)} \inf_k \min_{R_{-\ell}^{k+1} \subset Q_0^k} \frac{\text{dist}(R_{-\ell}^{k+1}, \partial Q_0^k)}{|Q_0^k|} = \epsilon_1 > 0.$$

Without loss of generality we can choose ϵ_0 in (60) satisfying $\epsilon_0 < \epsilon_1/4$. Let $\phi: \mathbb{R} \rightarrow \mathbb{R}$ be a C^∞ function such that

- i. $\phi(x) \in [0, 1]$ for every $x \in \mathbb{R}$.
- ii. If $|x| < 1 - \epsilon_1/4$ then $\phi(x) = 1$.
- iii. If $|x| > 1 - \epsilon_1/8$ then $\phi(x) = 0$.

Given $q \in C(F)$, let i_j be such that $q_{i_j}^j = q$ and $\delta_{i_j}^j$ and β_q^j , $j \in \mathbb{N}$, be as in the proof of Lemma 8.2. For every $x \in \mathbb{R}^*$ define

$$\psi_q(x) = \sum_{j=1}^{\infty} \frac{\partial_t \beta_q^j}{\beta_q^j} \cdot \phi\left(\frac{x}{\delta_{i_j}^j}\right)$$

The function ψ_q is well defined in $\mathbb{R} \setminus \{0\}$, it is C^∞ on $\mathbb{R} \setminus \{0\}$ and if

$$(80) \quad (1 - \epsilon_1/8)|\delta_{i_{k+1}}^{k+1}| \leq |x| \leq (1 - \epsilon_1/2)|\delta_{i_k}^k|$$

then

$$(81) \quad \psi_q(x) = \sum_{j=1}^k \frac{\partial_t \beta_q^j}{\beta_q^j} \cdot \phi\left(\frac{x}{\delta_{i_j}^j}\right) = \sum_{j=1}^k \frac{\partial_t \beta_q^j}{\beta_q^j} = \frac{\partial_t \delta_{i_k}^k}{\delta_{i_k}^k}.$$

Moreover, notice that if

$$(82) \quad |\delta_{i_{k+1}}^{k+1}| \leq |x| \leq |\delta_{i_k}^k|$$

then

$$\psi_q(x) = \frac{\partial_t \beta_q^k}{\beta_q^k} \cdot \phi\left(\frac{x}{\delta_{i_k}^k}\right) + \sum_{j=1}^{k-1} \frac{\partial_t \beta_q^j}{\beta_q^j},$$

so

$$D\psi_q(x) = \frac{\partial_t \beta_q^k}{\delta_{i_k}^k \beta_q^k} \cdot D\phi\left(\frac{x}{\delta_{i_k}^k}\right),$$

and by (72) and (82)

$$(83) \quad |D\psi_q(x)| \leq \frac{1}{|\delta_{i_k}^k|} C_3 \max |D\phi| \leq \frac{C_3 \max |D\phi|}{|x|}$$

If $q = (0, j)$, define

$$(84) \quad \alpha_2(z, j) = \psi_q(|z|)z.$$

By (83) and Lemma 8.4 we conclude that α_2 is a quasiconformal vector field with $\alpha_2(0, j) = 0$ for every j .

It remains to show that α_2 satisfies (78). Indeed, let $(z, j) \in \partial\mathcal{R}_{-\ell}^{k+1}$, with $R_{-\ell}^{k+1} \subset Q_0^k$ and $\ell > 0$. Since $\mathcal{R}_{-\ell}^{k+1}$ belongs to a disc with diameter given by the interval $R_{-\ell}^{k+1}$ and it does not intercept \mathcal{Q}_0^{k+1} , we have

$$(85) \quad (1 - \epsilon_1/64)|\delta_{i_{k+1}}^{k+1}| \leq d_q^{k+1} \leq |z| \leq (1 - \epsilon_1)|\delta_{i_k}^k|.$$

for every $(z, j) \in \partial\mathcal{R}_{-\ell}^{k+1}$. Here d_q^{k+1} is as defined in (61). By (81) we have that

$$\alpha_2(z, j) = \frac{\partial_t \delta_{i_k}^k}{\delta_{i_k}^k} z$$

for every

$$(z, j) \in \partial\mathcal{R}_{-\ell}^{k+1}.$$

Indeed, let $(z, \tilde{j}) \in \mathcal{R}_{-\ell}^{k+1}$, with $R_{-\ell}^{k+1} \subset S_0^k$, with $\ell > 0$ and such that q is the successor of s at level k . Then

$$G(\mathcal{R}_{-\ell}^{k+1}) \subset \mathcal{Q}_0^k.$$

If $G(\mathcal{R}_{-\ell}^{k+1}) = \mathcal{R}_{-a}^{k+1}$, for some $a > 0$, then the points in this image also satisfies (85). Otherwise $r = q$ and $G(\mathcal{R}_{-\ell}^{k+1}) = \mathcal{Q}_0^{k+1}$, so if $(w, j) \in G(\partial\mathcal{R}_{-\ell}^{k+1})$ then

$$(86) \quad (1 - \epsilon_1/64)|\delta_{i_{k+1}}^{k+1}| \leq |d_q^{k+1}| = |w| \leq |\delta_{i_{k+1}}^{k+1}| \leq (1 - \epsilon_1)|\delta_{i_k}^k|.$$

By (81) we have that

$$\alpha_2(w, j) = \frac{\partial_t \delta_{i_k}^k}{\delta_{i_k}^k} w$$

for every

$$(w, j) \in G(\partial\mathcal{R}_{-\ell}^{k+1}),$$

Since these estimates holds for every $q \in C(F)$ we have that for every $(z, j) \in \partial\mathcal{R}_{-\ell}^{k+1}$, with $R_{-\ell}^{k+1} \subset Q_0^k$ and $\ell > 0$ we have

$$\begin{aligned} \alpha_2 \circ G(z, j) - DG(z, j) \cdot \alpha_2(z, j) &= \frac{\partial_t \delta_{i_{k+1}}^k}{\delta_{i_{k+1}}^k} G(z, j) - DG(z, j) \frac{\partial_t \delta_{i_k}^k}{\delta_{i_k}^k} (z, j) \\ &= \frac{\partial_t \delta_{i_{k+1}}^k}{\delta_{i_{k+1}}^k} F^{n_{i_k}}(z, j) - DF^{n_{i_k}}(z, j) \frac{\partial_t \delta_{i_k}^k}{\delta_{i_k}^k} (z, j) \\ (87) \quad &= V_2(z, j). \end{aligned}$$

□

Proposition 8.6. *Let $v \in \mathfrak{B}_+(F)$. There exists a quasiconformal vector field $\alpha_1: \mathbb{C}_n \rightarrow \mathbb{C}$ such that*

$$(88) \quad V_1(z, j) = \alpha_1 \circ G(z, j) - DG(z, j) \cdot \alpha_1(z, j)$$

for every $(z, j) \in \partial\mathcal{D}$ and moreover $\alpha_1(q) = 0$ for every $q \in C(F)$.

Proof. Let $\epsilon_1 > 0$ be as in (79). Let $\phi: \mathbb{C} \rightarrow \mathbb{R}$ be a C^∞ function such that

- i. $\phi(x) \in [0, 1]$ for every $x \in \mathbb{C}$.

- ii. If $|x| = 1 - \epsilon_0/16$ and then $\phi(x) = 1$.
- iii. If either $|x| > 1 - \epsilon_0/32$, $|x| < 1 - \epsilon_1/2$ then $\phi(x) = 0$.

Given $r \in C(F)$, let

$$i_0 = 0 < i_1 < \dots < i_{\ell_r^k} < n_r^k$$

be the sequence of integers $i < n_r^k$ such that

$$R_i^k \subset \bigcup_{q \in C(F)} Q_0^{k-1}.$$

Denote by δ_r^k the periodic point in the boundary of R_0^k . There is an onto univalent extension

$$G^j : D_{r,-j}^k \rightarrow B(r, |\delta_r^k|),$$

where $D_{r,-j}^k \cap \mathbb{R} = R_{-i_j}^k$. Note that $\mathcal{R}_{-i_j}^k \subset D_{r,-j}^k$ and

$$(89) \quad G^j(\mathcal{R}_{-i_j}^k) = B(r, (1 - \epsilon_0/16)|\delta_r^k|) = \mathcal{R}_0^k.$$

Let $q_j \in C(F)$ such that q_j and $R_{-i_j}^k$ belongs to the same connected component of I_F^n . Define a function

$$\psi_{r,-j}^k : \mathbb{C}_n \rightarrow \mathbb{C}$$

in the following way. Let

$$\psi_{r,0}^k(z, a) = 0$$

for every $(z, a) \in \mathbb{C}_n$, and define by induction on j

$$(90) \quad \psi_{r,-(j+1)}^k(z, a) = \phi\left(\frac{G^{j+1}(z, a)}{\delta_r^k}\right) \frac{\psi_{r,-j}^k(G(z, a)) - \delta_{q_j}^{k-1} v^{k-1} \circ A_{q_{j+1}}^{k-1}(z, a)}{DG(z, a)}$$

for every $(z, a) \in D_{r,-(j+1)}^k$. Note that $\psi_{r,-(j+1)}^k(z, a) = 0$ for (z, a) in a neighbourhood of $\partial D_{r,-(j+1)}^k$, so we can extend $\psi_{r,-(j+1)}^k$ to a C^∞ function on \mathbb{C}_n defining $\psi_{r,-(j+1)}^k(z, a) = 0$ for $(z, a) \notin D_{r,-(j+1)}^k$. Finally note that by (89)

$$\phi\left(\frac{G^{j+1}(z, a)}{\delta_r^k}\right) = 1$$

for every $(z, a) \in \partial \mathcal{R}_{-i_{j+1}}^k$, so by (90)

$$(91) \quad -V_1(z, a) = \delta_{q_j}^{k-1} v^{k-1} \circ A_{q_{j+1}}^{k-1}(z, a) = \psi_{r,-j}^k(G(z, a)) - DG(z, a) \psi_{r,-(j+1)}^k(z, a)$$

for every $(z, a) \in \partial \mathcal{R}_{-i_j}^k$. Note that given $(z, a) \in \mathbb{C}_n \setminus C(F)$, there exists an open neighbourhood of (z, a) that intersects only one of the supports of a function in the family

$$\mathcal{F} = \{\psi_{r,-j}^k\}_{k, r \in C(F), j \leq \ell_r^k}.$$

In particular the function

$$\alpha_1(z, a) = - \sum_k \sum_{r \in C(F)} \sum_{j=0}^{\ell_r^k} \psi_{r,-j}^k(z, a)$$

is well defined and it is C^∞ on $\mathbb{C}_n \setminus C(F)$. Moreover given $\mathcal{R}_{-i_j}^k$, the function $\psi_{r,-j}^k$ is the unique function in this family whose support intersects $\partial \mathcal{R}_{-i_j}^k$. By (91), this implies that

$$V_1(z, a) = \alpha_1 \circ G(z, a) - DG(z, a) \alpha_1(z, a).$$

for every $(z, a) \in \partial\mathcal{D}$. It is easy to prove by induction that

$$(92) \quad |\psi_{r,-j}^k(z, a)| \leq \sup_k |v^{k-1}| \sum_{\ell=0}^{j-1} \frac{|\delta_{q_{j-1-\ell}}^{k-1}|}{|DG|^{\ell+1}(z, a)},$$

in particular

$$(93) \quad |\psi_{r,-j}^k| \leq \max_{q \in C(F)} |\delta_q^{k-1}| \sup_k |v^{k-1}| \sum_{j=0}^{\sup_k \frac{p_k}{p_{k-1}}} \frac{1}{(\inf |DG|)^j}.$$

Due the real bounds

$$(94) \quad |\psi_{r,-j}^k| \leq C\theta^{-k}$$

If $(z, a) \in \mathcal{Q}_0^{k-1} \setminus \{q\}$, for some $q \in C(F)$ then either $\alpha_1(z, a) = 0$ or (z, a) belongs to the support of a unique function $\psi_{r,-j}^b$, with $b \geq k$. We conclude that

$$(95) \quad \lim_{(z,a) \rightarrow q} \alpha_1(z, a) = 0,$$

so we can extend α_1 as a continuous function on \mathbb{C}_n . Note that

$$(96) \quad \begin{aligned} & \bar{\partial} \psi_{r,-(j+1)}^k(z, a) \\ &= \bar{\partial} \phi \left(\frac{G^{j+1}(z, a)}{\delta_r^k} \right) \frac{\overline{DG^{j+1}}(z, a)}{\bar{\delta}_r^k} \frac{\psi_{r,-j}^k(G(z, a)) - \delta_{q_j}^{k-1} v^{k-1} \circ A_{q_{j+1}}^{k-1}(z, a)}{DG(z, a)} \\ &+ \phi \left(\frac{G^{j+1}(z, a)}{\delta_r^k} \right) \bar{\partial} \psi_{r,-j}^k(G(z, a)) \frac{\overline{DG}(z, a)}{DG(z, a)} \end{aligned}$$

By the real bounds there exists $C > 0$ such that

$$\frac{|DG^{j-\ell}|(G^{\ell+1}(z, a))}{|\delta_r^k|} \leq \frac{C}{|R_{-i_{j-\ell}}^k|}$$

for every $r \in C(F)$, K and j and $(z, a) \in D_{r,-(j+1)}^k$. In particular

$$(97) \quad \begin{aligned} & \frac{|DG^{j+1}|(z, a)}{|\delta_r^k|} \frac{|\psi_{r,-j}^k(G(z, a)) - \delta_{q_j}^{k-1} v^{k-1} \circ A_{q_{j+1}}^{k-1}(z, a)|}{|DG(z, a)|} \\ &\leq \frac{|DG^{j+1}|(z, a)}{|\delta_r^k|} \left(\sum_{\ell=0}^{j-1} \frac{|\delta_{q_{j-1-\ell}}^{k-1}|}{|DG|^{\ell+2}(z, a)} + \frac{|\delta_{q_j}^{k-1}|}{|DG|(z, a)} \right) \\ &\leq \frac{|DG^{j+1}|(z, a)}{|\delta_r^k|} \sum_{\ell=0}^j \frac{|\delta_{q_{j-\ell}}^{k-1}|}{|DG|^{\ell+1}(z, a)} \\ &\leq \sum_{\ell=0}^j \frac{|DG^{j-\ell}|(G^{\ell+1}(z, a)) |\delta_{q_{j-\ell}}^{k-1}|}{|\delta_r^k|} \leq C \sum_{\ell=0}^j \frac{|\delta_{q_{j-\ell}}^{k-1}|}{|R_{-i_{j-\ell}}^k|} \\ &\leq C \sup_k \frac{\mu^{(k)}}{\mu^{(k-1)}}. \end{aligned}$$

The last inequality follows from the fact that $R_{-i_{j-\ell}}^k \subset Q_0^{k-1}$, with $q = q_{j-\ell}$, and $2\delta_{q_{j-\ell}}^{k-1} = |Q_0^{k-1}|$ and by the real bounds there exists $C > 0$ such that

$$\frac{|Q_0^{k-1}|}{|R_{-i}^k|} \leq C$$

for every $R_{-i}^k \subset Q_0^{k-1}$. So by (97)

$$(98) \quad \sup |\bar{\partial} \psi_{r, -(j+1)}^k| \leq C \sup |\bar{\partial} \phi| \sup_k \frac{\mu^{(k)}}{\mu^{(k-1)}} + \sup |\bar{\partial} \psi_{r, -j}^k|.$$

Since $\psi_0^k = 0$ we obtain

$$\sup |\bar{\partial} \psi_{r, -j}^k| \leq C \sup_k \frac{\mu^{(k)}}{\mu^{(k-1)}}$$

Since for every $(z, a) \in \mathbb{C}_n \setminus C(F)$, there exists an open neighbourhood of (z, a) that intersects only one of the supports of the functions in the family \mathcal{F} , we conclude that α_1 is a quasiconformal vector field on $\mathbb{C}_n \setminus C(F)$. Since α_1 is continuous at $C(F)$, we can use the argument in the end of the proof of Lemma 8.4 to conclude that α_1 is a quasiconformal vector field on \mathbb{C}_n . \square

Proof of Theorem 4. Let $v \in \mathfrak{B}_+(F)$. Let α_1 and α_2 as in Proposition 8.5 and 8.6. Define $\alpha^0 = \alpha_1 + \alpha_2$. Then by Lemma 8.1

$$(99) \quad V(z, j) = \alpha^0 \circ G(z, j) - DG(z, j) \cdot \alpha^0(z, j)$$

for every $(z, j) \in \partial \mathcal{D} \setminus C(F)$ and moreover $\alpha^0(q) = 0$ for every $q \in C(F)$. Now we will use an argument similar to the infinitesimal pullback argument for polynomial-like maps [3]. We define by induction on m a sequence of quasiconformal vector fields

$$\alpha^m: \mathbb{C}_n \rightarrow \mathbb{C}$$

such that $\alpha^m(q) = 0$ for every $q \in C(F)$,

$$(100) \quad V(z, j) = \alpha^m \circ G(z, j) - DG(z, j) \cdot \alpha^m(z, j)$$

for every $(z, j) \in \partial \mathcal{D}$ and moreover

$$(101) \quad V(z, j) = \alpha^{m-1} \circ G(z, j) - DG(z, j) \cdot \alpha^m(z, j)$$

for every $(z, j) \in \mathcal{D}$, $m \geq 1$ and

$$\sup_{\mathbb{C}_n} |\bar{\partial} \alpha^{m+1}| \leq \sup_{\mathbb{C}_n} |\bar{\partial} \alpha^m|.$$

Indeed, suppose by induction we have defined α^k . Define $\alpha^{k+1}(z, j) = \alpha^k(z, j)$ for every $(z, j) \notin \mathcal{D}$ and

$$(102) \quad \alpha^{k+1}(z, j) = \frac{\alpha^k(G(z, j)) - V(z, j)}{DG(z, j)}$$

for every $(z, j) \in \mathcal{D}$. Note that

$$|\bar{\partial} \alpha^{k+1}(z, j)| = |\bar{\partial} \alpha^k(z, j)|,$$

for every $(z, j) \notin \mathcal{D}$ and

$$|\bar{\partial} \alpha^{k+1}(z, j)| = |\bar{\partial} \alpha^k(G(z, j))|$$

for $(z, j) \in \mathcal{D}$. So α^{k+1} is a quasiconformal vector field in $\mathbb{C}_n \setminus \partial \mathcal{D}$. Moreover (101) holds for $m = k + 1$ and due (100) with $m = k$ we have that $\alpha^{k+1} = \alpha^k$ on $\partial \mathcal{D} \setminus C(F)$, so α^{k+1} is continuous at points in

$$\partial \mathcal{D} \setminus C(F).$$

If $(z, j) \in \partial \mathcal{D} \setminus C(F)$ then $(z, j) \in \partial \mathcal{R}_{-i}^n$, for some $r \in C(F)$. In particular there exists a neighbourhood W of (z, j) such that α^{k+1} is continuous on W and a quasiconformal vector field on $W \setminus \partial \mathcal{R}_{-i}^n$. Since $\partial \mathcal{R}_{-i}^n$ is an analytic curve we conclude that α^{k+1} is a quasiconformal vector field on W . So α^{k+1} is a quasiconformal vector field on $\mathbb{C}_n \setminus C(F)$. Finally notice that α^{k+1} is continuous at points in $C(F)$. Indeed, suppose that

$$(z_\ell, i) \rightarrow_\ell (0, i).$$

If $(z_\ell, i) \notin \mathcal{D}$ for every ℓ then

$$\lim_{\ell \rightarrow \infty} \alpha^{k+1}(z_\ell, i) = \lim_{\ell \rightarrow \infty} \alpha^k(z_\ell, i) = 0.$$

If $(z_\ell, i) \in \mathcal{D}$ for every ℓ then

$$(103) \quad \lim_{\ell \rightarrow \infty} \alpha^{k+1}(z_\ell, i) = \lim_{\ell \rightarrow \infty} \frac{\alpha^k(G(z_\ell, i)) - V(z_\ell, i)}{DG(z_\ell, i)}.$$

Since the accumulation points of the sequence $G(z_\ell, i)$ belongs to $C(F)$ we have

$$\lim_{\ell \rightarrow \infty} \alpha^k(G(z_\ell, i)) = 0.$$

By Lemma 8.3 it follows that

$$\lim_{\ell \rightarrow \infty} V(z_\ell, i) = 0.$$

Since by the complex bounds we have that

$$\inf_{(z, j) \in \mathcal{D}} |DG(z, j)| > 0$$

we conclude by (103) that

$$\lim_{\ell \rightarrow \infty} \alpha^{k+1}(z_\ell, i) = 0.$$

so α^{k+1} is continuous at points in $C(F)$. By the same argument in the end of the proof of Lemma 8.4 we conclude that α^{k+1} is a quasiconformal vector field on \mathbb{C}_n and

$$(104) \quad \sup_{\mathbb{C}_n} |\bar{\partial} \alpha^{k+1}| \leq \sup_{\mathbb{C}_n} |\bar{\partial} \alpha^k|.$$

Given a point $(z, j) \in \mathbb{C}_n$ such that there exists $k_0 \geq 0$ such that $G^k(z, j) \in \mathcal{D}$ for every $k < k_0$ and $G^{k_0}(z, j) \notin \mathcal{D}$, we claim that $\alpha^k(z, j) = \alpha^{k_0}(z, j)$ for every $k \geq k_0$. Note that $\alpha^k(z, j) = \alpha^0(z, j)$ for every $(z, j) \notin \mathcal{D}$, so the claim holds for $k_0 = 0$. Suppose by induction on k_0 that the claim hold for k_0 . If $G^i(z, j) \in \mathcal{D}$ for $i \leq k_0$ and $G^{k_0+1}(z, j) \notin \mathcal{D}$ then $G^i(G(z, j)) \in \mathcal{D}$ for $i < k_0$ and $G^{k_0}(G(z, j)) \notin \mathcal{D}$, so by the induction assumption $\alpha^k(G(z, j)) = \alpha^{k_0}(G(z, j))$ for every $k \geq k_0$. Since $G(z, j) \in \mathcal{D}$ we have by (102) that

$$\alpha^{k+1}(z, j) = \frac{\alpha^k(G(z, j)) - V(z, j)}{DG(z, j)} = \frac{\alpha^{k_0}(G(z, j)) - V(z, j)}{DG(z, j)} = \alpha^{k_0+1}(z, j),$$

for every $k \geq k_0$, which proves the claim.

By Proposition 6.2 the sequence α^k converges almost everywhere. By (104) and McMullen [32] we have that every subsequence α^k has a subsequence that converges uniformly to some quasiconformal vector field. So α^k converges uniformly to a quasiconformal vector field α . Taking $m \rightarrow \infty$ in (101) we conclude that

$$(105) \quad V(z, j) = \alpha \circ G(z, j) - DG(z, j) \cdot \alpha(z, j),$$

for every $(z, j) \in \mathcal{D}$ and in particular for every $(z, j) \in P(F) \setminus C(F)$. Since $\alpha(q) = 0$ for every $q \in C(F)$, by Corollary 7.3 we conclude that $v \in E^h(F)$. \square

9. TRANSVERSAL FAMILIES HAVE HYPERBOLIC PARAMETERS.

From now on we will consider only *real maps*. In particular $\mathcal{B}_{nor}^{\mathbb{R}}(U)$ will now denote the real Banach space of all $F \in \mathcal{B}_{nor}(U)$ which are real on the real line. Since $\Omega_{n,p}$ is a hyperbolic set we can define the stable

$$G \mapsto E_G^h$$

and unstable

$$G \mapsto E_G^u$$

subspace distributions defined for $G \in \Omega_{n,p}$, and the corresponding projections on the spaces

$$\pi_G^h: T\mathcal{B}_{nor}^{\mathbb{R}}(U) \rightarrow E_G^h$$

and

$$\pi_G^u: T\mathcal{B}_{nor}^{\mathbb{R}}(U) \rightarrow E_G^u.$$

Recall that $U = D_{\delta_0, \theta_0}$. As defined in [43] we also have the adapted norms $|\cdot|_{G,0}$ that satisfy

$$|v|_{G,0} = |\pi_G^h(v)|_{G,0} + |\pi_G^u(v)|_{G,0},$$

and the family of cones $C_\epsilon^u(G)$, with $\epsilon > 0$, for which $v \in C_\epsilon^u(G)$ if and only if

$$|\pi_G^h(v)|_{G,0} \leq \epsilon |\pi_G^u(v)|_{G,0}.$$

Those cones are unstable and forward-invariant for the action of \mathcal{R} on $\Omega_{n,p}$ provided ϵ is small enough. In particular if ϵ is small there is $\theta > 1$ such that for every $F \in \mathcal{B}_{nor}^{\mathbb{R}}(U)$ close enough to some $G \in \Omega_{n,p}$, and $v \in C_{2\epsilon}^u(G)$

$$|D\mathcal{R}_F \cdot v|_{\mathcal{R}G,0} \geq \theta |v|_{G,0}.$$

and moreover there is $\epsilon' \in (0, \epsilon)$ such that

$$|\pi_{\mathcal{R}G}^h(D\mathcal{R}_F \cdot v)|_{\mathcal{R}G,0} \leq 2\epsilon' |\pi_{\mathcal{R}G}^u(D\mathcal{R}_F \cdot v)|_{\mathcal{R}G,0}.$$

Furthermore there is $\lambda \in (0, 1)$ such that for every $G \in \Omega_{n,p}$, $v \in E_G^h$ and $k \in \mathbb{N}$

$$|D\mathcal{R}_G^k \cdot v|_{\mathcal{R}^k G,0} \leq \lambda^k |v|_{G,0}.$$

Define the δ -shadow of G as

$$W_\delta^s(G) = \{F \in \mathcal{W}: \text{dist}_{\mathcal{B}_{nor}^{\mathbb{R}}(U)}(\mathcal{R}^k F, \mathcal{R}^k G) \leq \delta, \text{ for every } k \geq 0\},$$

and the δ -shadow of $\Omega_{p,n}$ as

$$W_\delta^s(\Omega_{p,n}) = \cup_{G \in \Omega_{p,n}} W_\delta^s(G).$$

We also define

$$\mathbb{B}_G^u(v_0, \delta) = \{v \in E_G^u \cap \mathcal{B}^{\mathbb{R}}(U): |v - v_0|_{G,0} \leq \delta\},$$

where $v_0 \in E_G^u \cap \mathcal{B}^{\mathbb{R}}(U)$, and

$$E_G^h + G = \{v + G: v \in E_G^h\}.$$

Let $\delta_3 > 0$ (we will use this notation to follow [43]). Define $\mathcal{T}_0^1(G, \delta, \epsilon)$, with $\delta \in (0, \delta_3)$, as the set of C^1 functions

$$\mathcal{H}: \mathbb{B}_G^u(v_0, \delta) \rightarrow E_G^h + G,$$

with $v_0 \in E_G^u \cap \mathcal{B}^{\mathbb{R}}(U)$, such that

$$|D\mathcal{H}|_{(G,0),(G,0)} \leq \epsilon.$$

and

$$F_0 = v_0 + \mathcal{H}(v_0) \in W_{\delta_3}^s(G).$$

We will call F_0 the *base point* of \mathcal{H} . In particular $w + D_x \mathcal{H} \cdot w \in C^u(G)$, for every $x \in \mathbb{B}_G^u(v_0, \delta)$, $w \in E^u(G)$, and $G \in \Omega_{p,n}$.

Denote

$$\hat{\mathcal{H}} = \{v + \mathcal{H}(v) : v \in \mathbb{B}_G^u(v_0, \delta)\}.$$

The Transversal Empty Interior assumption for the renormalization operator is the main result of this section.

Corollary 9.1 (Transversal Empty Interior Assumption). *For every small $\epsilon > 0$ we can choose δ_3 small enough such that the following holds. For every $G \in \Omega_{p,n}$ and for every C^{1+Lip} function $\mathcal{H} \in \mathcal{T}_0^1(G, \delta', \epsilon)$, with $\delta' < \delta_3$, we have that $\hat{\mathcal{H}} \cap W_{\delta_3}^s(\Omega)$ has empty interior in $\hat{\mathcal{H}}$.*

This property is closely related with the fact that maps F that are infinitely renormalizable with bounded combinatorics can be approximated by hyperbolic maps.

We are going to introduce notation from [43]. Denote by $C^{\omega_{\mathbb{R}}}([-1, 1]^j, \mathcal{B}_{nor}^{\mathbb{R}}(U))$ the space of functions

$$\gamma : (-1, 1)^j \rightarrow \mathcal{B}_{nor}^{\mathbb{R}}(U)$$

which can be extended to a complex analytic function

$$\gamma : \mathbb{D}^j \rightarrow \mathcal{B}_{nor}(U),$$

and moreover there is a continuous extension of γ to $\overline{\mathbb{D}}^j$. Endowed with the sup norm on $\overline{\mathbb{D}}^j$ the space $C^{\omega_{\mathbb{R}}}([-1, 1]^j, \mathcal{B}_{nor}^{\mathbb{R}}(U))$ is a real Banach space.

Endow $T_{\mathbb{C}} = \overline{\mathbb{D}}^{\mathbb{N}}$ with the product topology. Let $\Gamma^{\omega}(\mathcal{B}_{nor}(U))$ be the set of continuous functions $\gamma : T_{\mathbb{C}} \rightarrow \mathcal{B}_{nor}(U)$ which are holomorphic when we fix all but a finite number of entries of $\lambda \in T_{\mathbb{C}}$ and $|\lambda_i| < 1$ for every i . Endowing $\Gamma^{\omega}(\mathcal{B}_{nor}(U))$ with the sup norm we obtain a complex Banach space.

Note that since U is symmetric with respect to the real line, that is, $(z, i) \in U$ iff $(\bar{z}, i) \in U$, there is a complex conjugation on the complex Banach space $\mathcal{B}(U)$ defined by $\overline{f}(z) = \overline{f(\bar{z})}$ for $f \in \mathcal{B}(U)$. Define $\Gamma^{\omega_{\mathbb{R}}}(\mathcal{B}_{nor}^{\mathbb{R}}(U))$ as the *real* Banach space that consists of the restrictions to $T = [-1, 1]^{\mathbb{N}}$ of functions $\gamma \in \Gamma^{\omega}(\mathcal{B}_{nor}(U))$ satisfying $\gamma(\bar{\lambda}) = \overline{\gamma(\lambda)}$.

We say that a set $\Theta \subset \mathcal{B}_{nor}(U)$ is a $\Gamma^{\omega_{\mathbb{R}}}(\mathcal{B}_{nor}^{\mathbb{R}}(U))$ -null set if there exists a residual subset $\mathcal{F} \subset \Gamma^{\omega_{\mathbb{R}}}(\mathcal{B}_{nor}^{\mathbb{R}}(U))$ such that

$$m(\lambda \in [-1, 1]^{\mathbb{N}} : \gamma(\lambda) \in \Theta) = 0$$

for every $\gamma \in \mathcal{F}$. Here m is the product measure obtained considering the normalised Lebesgue measure on each copy of $[-1, 1]$.

The Transversal Empty Interior property will allow us to apply [43, Theorem 1] to the renormalization operator. Indeed we already verified that

- $\mathcal{R} : \mathcal{W}^{\mathbb{R}} \rightarrow \mathcal{B}_{nor}^{\mathbb{R}}(U)$ is a real analytic map. Here $\mathcal{W}^{\mathbb{R}} = \mathcal{W} \cap \mathcal{B}_{nor}^{\mathbb{R}}(U)$.
- The map \mathcal{R} is a strongly compact operator (Remark 3.1),
- $\Omega_{n,p}$ is a hyperbolic set (Theorem 5),

- For every $F \in \mathcal{R}^{-i}W_\delta^s(\Omega_{n,p})$, with $i \in \mathbb{N}$ and $\delta > 0$, we have that $D_F \mathcal{R}^i(T_F \mathcal{B}_{nor}^\mathbb{R}(U))$ is dense in $T_{\mathcal{R}^i F} \mathcal{B}_{nor}^\mathbb{R}(U)$. This is an easy consequence of Theorem 3.

so [43, Theorem 1] in our setting boils down to

Theorem 6. ([43, Theorem 1]) *Suppose that the renormalization operator \mathcal{R} satisfies additionally*

- A. *There exists $\delta_3 > 0$ such that $W_{\delta_3}^s(\Omega_{n,p})$ satisfies the Transversal Empty Interior assumption.*

Then $W^s(\Omega_{n,p})$ is a $\Gamma^{\omega_\mathbb{R}}(\mathcal{B}_{nor}^\mathbb{R}(U))$ -null set. Indeed for every j there exists a residual set of real-analytic maps $\gamma \in C^{\omega_\mathbb{R}}([-1, 1]^j, \mathcal{B}_{nor}^\mathbb{R}(U))$ such that

$$m(t \in [-1, 1]^j : \gamma(t) \in W^s(\Omega_{n,p})) = 0.$$

Here m is the Lebesgue measure on $[-1, 1]^j$.

In particular this implies that a generic real-analytic finite-dimensional family in $\mathcal{W}^\mathbb{R}$ intersects $W^s(\Omega_{n,p})$ on a subset with zero Lebesgue measure. So we have a version of Theorem A. for real-analytic families of extended maps that belong to $\mathcal{W}^\mathbb{R}$. Indeed the full-blown version of Theorem A. is proven in Section 10.

Proposition 9.2. *For every $\epsilon > 0$ small enough there is $\gamma > 0$ with the following property. Suppose that $F \in \mathcal{B}_{nor}^\mathbb{R}(U)$, that F has a polynomial-like extension $F: \hat{V}^0 \rightarrow \hat{V}^1$, with $\bar{U} \subset \hat{V}^0$, and*

$$\text{dist}_{\mathcal{B}_{nor}^\mathbb{R}(U)}(F, G) < \gamma,$$

for some $G \in \Omega_{p,n}$. If

$$v \in \hat{E}_F^h \cap C_{2\epsilon}^u(G)$$

and $v \in \mathcal{B}^\mathbb{R}(\hat{V}^0) \cap \mathcal{B}^\mathbb{R}(U)$ then $v = 0$.

Proof. Suppose by contradiction that there exist sequences $G_i \in \Omega_{p,n}$, $F_i \in \mathcal{B}_{nor}^\mathbb{R}(U)$ and $v_i \in \mathcal{B}^\mathbb{R}(\hat{V}_i^0)$ such that

- We have

$$\text{dist}_{\mathcal{B}_{nor}^\mathbb{R}(U)}(F_i, G_i) \rightarrow_i 0,$$

- The maps F_i have a polynomial-like of type n extension $F_i: \hat{V}_i^0 \rightarrow \hat{V}_i^1$ and $\bar{U} \subset \hat{V}_i^0$.
- The vectors satisfy $v_i \in \hat{E}_{F_i}^h \cap C_{2\epsilon}^u(G_i)$, $|v_i|_{\mathcal{B}^\mathbb{R}(U)} \neq 0$ and $v_i \in \mathcal{B}^\mathbb{R}(\hat{V}_i^0)$.

In particular for large i the critical points of F_i belongs to $K(F_i)$ and F_i is renormalizable. Without loss of generality we can assume that $|v_i|_{\mathcal{B}(U)} = 1$ for every i . Since $v_i \in \hat{E}^h(F_i)$ and F_i are very close to $\Omega_{n,p}$ we have that $\mathcal{R}F_i$ has a polynomial-like extension of type n

$$\mathcal{R}F_i: V_i^0 \rightarrow V_i^1$$

with $\text{mod } V_i^1 \setminus V_i^0 > \epsilon_0$. Moreover $D_{F_i} \mathcal{R} \cdot v_i \in \hat{E}_{\mathcal{R}F_i}^h \cap \mathcal{B}^\mathbb{R}(V_i^0)$ and there is $C > 0$ such that

$$|D_{F_i} \mathcal{R} \cdot v_i|_{\mathcal{B}^\mathbb{R}(V_i^0)} \leq C$$

for every large i . Note that $\mathcal{R}F_i: V_i^0 \rightarrow V_i^1$ is real on the real line and consequently it is hybrid conjugate with a real polynomial of type n (see the Straightening lemma in [40, Proposition 4.1]). It follows from Shen [37] that $\mathcal{R}F_i$ does not have invariant line fields on its Julia set. So one can use the infinitesimal pullback

argument to conclude that there exist quasiconformal vector fields $\alpha_i: \mathbb{C}_n \rightarrow \mathbb{C}$ with $\sup_i |\bar{\partial}\alpha_i|_\infty < \infty$ such that

$$(106) \quad D_{F_i} \mathcal{R} \cdot v_i = \alpha_i \circ \mathcal{R}F_i - D(\mathcal{R}F_i) \cdot \alpha_i$$

on a domain a little bit smaller than V_i^0 , and in particular on $U = D_{\delta_0, \theta_0}$. By a compactness argument [32] the sequence α_i has a convergent subsequence that converges to a quasiconformal vector field α . Let

$$D_\delta = \{x \in \mathbb{C} : \text{dist}(x, [-1, 1]) < \delta\} \times \{1, \dots, n\}.$$

Note that by (13) there exists $\delta' > \delta_0$ such that $\bar{U} \subset D_{\delta'} \subset V_i^0$ for every i . Since

$$|D_{F_i} \mathcal{R} \cdot v_i|_{\mathcal{B}(D_{\delta'})} \leq C,$$

there exists a subsequence of $D_{F_i} \mathcal{R} \cdot v_i$ that converges to some v on $\mathcal{B}^{\mathbb{R}}(U)$ satisfying $|v|_{\mathcal{B}(U)} \leq C$. Since $\Omega_{p,n}$ is compact, without loss of generality we can assume that $\mathcal{R}G_i$ (and so $\mathcal{R}F_i$) converges to some $G \in \Omega_{p,n}$. By (106) we obtain

$$v = \alpha \circ G - DG \cdot \alpha$$

on the pos-critical set of G . Since there are not invariant line fields supported in the Julia set of G , by the infinitesimal pullback argument we conclude that $v \in E_G^h$. In particular

$$(107) \quad |D\mathcal{R}_G^k \cdot v|_{\mathcal{R}^k(G),0} \leq \lambda^k |v|_{G,0} \leq C_1 \lambda^k.$$

On the other hand since $v_i \in C_{2\epsilon}^u(G_i)$ and ϵ is small we have

$$|D_{G_i} \mathcal{R} \cdot v_i|_{\mathcal{R}(G_i),0} \geq \theta |v_i|_{G_i,0} \geq C_2 \theta |v_i|_{\mathcal{B}^{\mathbb{R}}(U)} = C_2 \theta > 0,$$

The compactness of $\Omega_{p,n}$ gives $\lim_i D_{G_i} \mathcal{R} \cdot v_i = v$ and consequently for every $k \geq 1$

$$\lim_i D\mathcal{R}_{G_i}^k \cdot v_i = D\mathcal{R}_G^{k-1} \cdot v$$

and we have that $v_i \in C_{2\epsilon}^u(G_i)$ so for $k \geq 1$

$$|D\mathcal{R}_{G_i}^k \cdot v_i|_{\mathcal{R}^k(G_i),0} \geq \theta^{k-1} |D\mathcal{R}_{G_i} \cdot v_i|_{\mathcal{R}G_i,0} \geq C_2 \theta^k.$$

Taking the limit on i we obtain

$$(108) \quad |D\mathcal{R}_G^k \cdot v|_{\mathcal{R}^k(G),0} \geq C_2 \theta^k.$$

Since $\lambda < 1 < \theta$ we conclude that (107) and (108) give us a contradiction. \square

Proposition 9.3. *For $\epsilon > 0$ small we can choose δ_3 small enough such that for every $\delta' \in (0, \delta_3)$ the following holds. Let \mathcal{H} be a C^{1+Lip} function*

$$\mathcal{H}: \mathbb{B}_G^u(u_0, \delta') \rightarrow E_G^h + G$$

such that $\mathcal{H} \in \mathcal{T}_0^1(G, \delta', 2\epsilon)$, where $G \in \Omega_{p,n}$. Then there exists $w \in \mathbb{B}_G^u(u_0, \delta')$ such that $w + \mathcal{H}(w)$ is a map whose critical points belong to the same periodic orbit.

Proof. Define

$$\tilde{\mathcal{H}}: \mathbb{B}_G^u(u_0, \delta') \times \{v \in E^h(G) : |v| \leq \delta'\} \rightarrow \mathcal{B}_{nor}^{\mathbb{R}}(U)$$

as $\tilde{\mathcal{H}}(u, v) = u + \mathcal{H}(u) + v$. Let $F = u_0 + \mathcal{H}(u_0)$. Note that $\tilde{\mathcal{H}}$ is a homeomorphism on its image, which is an open neighbourhood of F . Define $\tilde{\mathcal{H}}_1(u, v) = \mathcal{R}\tilde{\mathcal{H}}(u, v)$. If δ_3 is small enough there is a smooth family of domains $\hat{U}_{(u,v)}$ such that for every (u, v) in the domain of $\tilde{\mathcal{H}}_1$ we have that

$$\tilde{\mathcal{H}}_1(u, v): \hat{U}_{(u,v)} \rightarrow \hat{V}$$

is a polynomial-like map of type n such that

$$\text{mod } \hat{V} \setminus \hat{U}_{(u,v)} > \epsilon_0.$$

Reducing \hat{V} a little bit, for every

$$(w, z) \in E^u(G) \times E^h(G)$$

we have

$$D_u \tilde{\mathcal{H}}_1(u, v) \cdot w + D_v \tilde{\mathcal{H}}_1(u, v) \cdot z \in \mathcal{B}(\hat{U}_{(u,v)}).$$

Moreover if $w \in E^u(G) \setminus \{0\}$ we have

$$D_u \tilde{\mathcal{H}}_1(u, v) \cdot w \in C_{2\epsilon}^u(\mathcal{R}G),$$

so by Proposition 9.2,

$$(109) \quad D_u \tilde{\mathcal{H}}_1(u, v) \cdot w \notin E_{\tilde{\mathcal{H}}_1(u,v)}^h,$$

and moreover for every $(w, z) \in E^u(G) \times E^h(G)$ such that

$$D_u \tilde{\mathcal{H}}_1(u, v) \cdot w + D_v \tilde{\mathcal{H}}_1(u, v) \cdot z \in E_{\tilde{\mathcal{H}}_1(u,v)}^h,$$

we have

$$(110) \quad D_u \tilde{\mathcal{H}}_1(u, v) \cdot w + D_v \tilde{\mathcal{H}}_1(u, v) \cdot z \notin C_{2\epsilon}^u(\mathcal{R}G).$$

The image of $\tilde{\mathcal{H}}$ is an open neighbourhood of $u_0 + \mathcal{H}(u_0) \in W_{\delta_3}^s(G)$, with $G \in \Omega_{n,p}$, in particular by Proposition 4.7 there exists (u_1, v_1) such that $\tilde{\mathcal{H}}(u_1, v_1)$ is a map whose critical points belong to the same periodic orbit, and consequently $\tilde{\mathcal{H}}_1(u_1, v_1) = \mathcal{R}\tilde{\mathcal{H}}(u_1, v_1)$ is also a map whose critical points belong to the same periodic orbit. Furthermore one can choose (u_1, v_1) arbitrarily close to $(u_0, 0)$. If $v_1 = 0$ choose $w = u_1$ and we finished the proof in this case. Otherwise $v_1 \neq 0$ and we consider the C^{1+Lip} smooth map

$$(u, t, x) \in E^u(G) \times \mathbb{R} \times U \mapsto f_{(u,t)}(x) := \tilde{\mathcal{H}}_1(u, tv_1)(x).$$

The critical points of $f_{(u_1,1)}$ belong to the same periodic orbit, so there are natural numbers i_k , $k = 1, \dots, n$ and we can index the critical points

$$Crit = \{(0, j)\}_{0 \leq j \leq n-1} = \{(0, j_k)\}_{0 \leq k \leq n-1}$$

in such way that for every $k \leq n-1$

$$f_{(u_0,1)}^{i_k}(0, j_k) = (0, j_{k+1 \bmod n}) \text{ and } f_{(u_0,1)}^i(0, j_k) \notin Crit \text{ for } i < i_k.$$

We claim that there is a function $t \mapsto u(t)$, defined for every $t \in [0, 1]$ such that

$$(111) \quad f_{(u(t),t)}^{i_k}(0, j_k) = (0, j_{k+1 \bmod n}) \text{ and } f_{(u(t),t)}^i(0, j_k) \notin Crit \text{ for } i < i_k,$$

for every $k \leq n-1$. Indeed, let Y be the set of $q \in [0, 1]$ such that there exists a continuous function u defined on $[q, 1]$ such that (111) holds for every $t \in [q, 1]$ and $u(1) = u_1$. Note that $1 \in Y$. We need to show that $0 \in Y$. It is enough to show that Y is a open and closed subset of $[0, 1]$. Indeed, suppose that (u_2, t_2) satisfies

$$(112) \quad f_{(u_2,t_2)}^{i_k}(0, j_k) = (0, j_{k+1 \bmod n}) \text{ and } f_{(u_2,t_2)}^i(0, j_k) \notin Crit \text{ for } i < i_k,$$

for every $k \leq n-1$. Note that the linear map

$$w \mapsto (D_u f_{(u_2,t_2)}^{i_k}(0, j_k) \cdot w)_{0 \leq k \leq n-1}$$

is invertible, otherwise it would exists $w \in E^u(G) \setminus \{0\}$ such that

$$D_u f_{(u_2,t_2)}^{i_k}(0, j_k) \cdot w = 0$$

for every k , so using the infinitesimal pullback argument one can conclude that

$$D_u \tilde{\mathcal{H}}_1(u_2, t_2 v_1) \cdot w \in E_{\tilde{\mathcal{H}}_1(u_2, t_2 v_1)}^h,$$

which contradicts (109). So by the Implicit Function Theorem there exists an open interval O with $t_2 \in O$ such that there is a unique continuous function u defined on O such that (111) holds for every $t \in O$ and $u(t_2) = u_2$. We conclude that Y is an open set and that for each $q \in Y$ there exists a *unique* continuous function U defined on $[q, 1]$ and satisfying (111) and $u(1) = u_1$. To show that Y is closed, suppose that $q_n \in Y$ is a decreasing sequence converging to some $q \in [0, 1]$. Then there exists a unique continuous function u defined in $(q, 1]$ such that $u(1) = u_1$ and (111) holds. We claim that u is a Lipchitz function on $(q, 1]$, so we can extend it to a continuous function u defined in $[q, 1]$. Indeed note that

$$\partial_t f_{(u(t), t)} \in E_{f_{(u(t), t)}}^h,$$

so by (110)

$$(113) \quad \partial_t f_{(u(t), t)} \notin C_{2\epsilon}^u(\mathcal{R}G).$$

Moreover

$$(114) \quad \partial_t f_{(u(t), t)} = D\mathcal{R}_{u(t)+\mathcal{H}(u(t))+tv_1} \cdot (u'(t) + D_u \mathcal{H}_{u(t)} \cdot u'(t) + v_1)$$

Let

$$y = D\mathcal{R}_{u(t)+\mathcal{H}(u(t))+tv_1} \cdot (u'(t) + D_u \mathcal{H}_{u(t)} \cdot u'(t)).$$

Note that

$$|y|_{\mathcal{R}G, 0} \geq \lambda \frac{1-2\epsilon}{1+2\epsilon} |u'(t)|_{G, 0}$$

Suppose that $|u'(t)|_{G, 0} \geq L|v_1|_{G, 0}$. If δ' is small enough then there is $C > 0$ such that

$$(115) \quad |\pi_{\mathcal{R}G, 0}^u(\partial_t f_{(u(t), t)})|_{\mathcal{R}G, 0} \geq \left(1 - \frac{C}{L\lambda} \frac{1+2\epsilon}{1-2\epsilon}\right) |y|_{\mathcal{R}G, 0},$$

and

$$(116) \quad |\pi_{\mathcal{R}G, 0}^h(\partial_t f_{(u(t), t)})|_{\mathcal{R}G, 0} \leq \left(2\epsilon' + \frac{C}{L\lambda} \frac{1+2\epsilon}{1-2\epsilon}\right) |y|_{\mathcal{R}G, 0}.$$

If L is large enough then

$$2\epsilon' + \frac{C}{L\lambda} \frac{1+2\epsilon}{1-2\epsilon} \leq 2\epsilon \left(1 - \frac{C}{L\lambda} \frac{1+2\epsilon}{1-2\epsilon}\right),$$

which implies that $\partial_t f_{(u(t), t)} \in C_{2\epsilon}^u(\mathcal{R}G)$. This contradicts (113). In particular there is L satisfying $|u'(t)|_{G, 0} \leq L|v_1|_{G, 0}$ for every $t \in (q, 1]$ and consequently u is a Lipchitz function. So we can extend u to a continuous map to $[q, 1]$. It is easy to see that (111) also holds for $t = q$. We conclude that Y is closed. Since Y is an open, closed, non empty subset of $[0, 1]$ we conclude that $Y = [0, 1]$, so in particular $0 \in Y$ and therefore there exists w such that $f_{(w, 0)} = \tilde{\mathcal{H}}_1(w, 0) = \mathcal{R}(w + \mathcal{H}(w))$ is a map whose critical points belong to the same periodic orbit, and consequently $w + \mathcal{H}(w)$ has the same property. \square

Proof of Corollary 9.1. Let ϵ be small. It is easy to see that if $\delta_3 > 0$ is small enough then for every $G \in \Omega_{p, n}$ and for every C^{1+Lip} function $\mathcal{H} \in \mathcal{T}_0^1(G, \delta', \epsilon)$, with $\delta' < \delta_3$ and for every

$$F \in \hat{\mathcal{H}} \cap W_{\delta_3}^s(\Omega_{n, p}),$$

there is $G_F \in \Omega_{n,p}$ such that $F \in W_{\delta_3}^s(G_F)$ and $\delta'' > 0$ such that

$$\{w + \mathcal{H}(w) : w \in \mathbb{B}^u(v_0, \delta')\} \cap \{u + v + G_F : u \in \mathbb{B}_{G_F}^u(\pi_{G_F}^u(F - G_F), \delta''), v \in E_{G_F}^h\}$$

is the graph $\hat{\mathcal{H}}_F$ of a C^{1+Lip} function in $\mathcal{T}_0^1(G_F, \delta'', 2\epsilon)$. By Proposition 9.3 there is $w \in \mathbb{B}_{G_F}^u(\pi_{G_F}^u(F - G_F), \delta'')$ such that $w + \mathcal{H}_F(w)$ is a map such that all its critical points belong to the same periodic orbit. In particular every map close enough to $w + \mathcal{H}_F(w)$ is a hyperbolic map with an attracting periodic orbit that attracts all its critical points. In particular we can find hyperbolic maps in $\hat{\mathcal{H}}$ arbitrarily close to F . Note that hyperbolic maps do not belong to $W_{\delta_3}^s(\Omega_{n,p})$, since every map in $W_{\delta_3}^s(\Omega_{n,p})$ is infinitely renormalizable. \square

10. FAMILIES OF MULTIMODAL MAPS

In the beginning of Section 9 we saw that a version of Theorem A. for real-analytic families of extended maps that *belong* to $\mathcal{W}^{\mathbb{R}}$ can be obtained from the hyperbolicity of $\Omega_{n,p}$, the Empty Interior Transversality property and [43, Theorem 1]. This is not enough to our purposes, once Theorem A. deals with real-analytic families of multimodal maps. Indeed a multimodal map with more than a critical point is *not* an extended map.

To prove Theorem A. we will need a classic tool, *inducing*. We will associate to each real-analytic multimodal map f that is close enough to an infinitely renormalizable multimodal map with bounded combinatorics a renormalization F of f , that is an extended map in $\mathcal{W}^{\mathbb{R}}$. Indeed a renormalizable multimodal map can be renormalizable in many ways (it can have distinct cycles of restrictive intervals with disjoint orbits) and many times (it can have deeper and deeper renormalizations), so we need to *mark* f with a restrictive interval P in such way to make this association

$$(f, P) \mapsto \mathcal{I}(f, P) = F$$

well-behaved. Indeed we are going to see that \mathcal{I} can be defined in such way that it is a real-analytic map defined in an open set of a real Banach space with image in $\mathcal{W}^{\mathbb{R}}$. The derivative $D_{(f,P)}\mathcal{I}$ of this map has dense image at every infinitely renormalizable marked multimodal maps (f, P) , which allows us to use Proposition 8.1 of [43] to conclude that $\mathcal{I}^{-1}W_{\delta}^s(\Omega_{n,p})$ intersects a generic real-analytic family of multimodal maps on a set of parameters with zero Lebesgue measure. This is the main argument of the proof of Theorem A. We provide the complete proof below.

Let $V \subset \mathbb{C}$ be a connected open set, symmetric with respect to the real line ($z \in V$ implies $\bar{z} \in V$) such that $[-1, 1] \subset V$. In this section we will denote by $\mathcal{B}_{\mathbb{C}}$ by affine subspace of $\mathcal{B}(V)$ defined by the restrictions $f(-1) = f(1) = -1$. Denote by $\mathcal{B}_{\mathbb{R}}$ the real Banach space of all functions $f \in \mathcal{B}_{\mathbb{C}}$ that are real on the $V \cap \mathbb{R}$.

Given $m \in \mathbb{N}$, let $\Gamma_m^{\omega_{\mathbb{R}}}(\mathcal{B}_{\mathbb{R}})$ be the set of all continuous functions

$$\gamma : \overline{\mathbb{D}}^m \rightarrow \mathcal{B}_{\mathbb{C}}$$

that are complex analytic on \mathbb{D}^m and such that $\gamma(\lambda) \in \mathcal{B}_{\mathbb{R}}$ for every $\lambda \in [-1, 1]^m$. We can endow $\Gamma_m^{\omega_{\mathbb{R}}}(\mathcal{B}_{\mathbb{R}})$ with the sup norm.

Let $\Gamma \subset \mathcal{B}_{\mathbb{R}}$ be the open subset of multimodal maps $f : [-1, 1] \rightarrow [-1, 1]$, where -1 is a repelling fixed point, $f'(1) \neq 0$, with quadratic critical points, negative schwarzian derivative and $f(-1, 1) \subset (-1, 1)$.

Denote by $\Gamma_n \subset \Gamma_n^{\omega_{\mathbb{R}}}(\mathcal{B}_{\mathbb{R}})$ the subset of all families γ such that $\gamma(\lambda) \in \Gamma$ for every $\lambda \in [-1, 1]^n$. Note that Γ_n is an open subset of $\Gamma_n^{\omega_{\mathbb{R}}}(\mathcal{B}_{\mathbb{R}})$.

10.1. Generic families. Our main result for generic families is

Theorem 7 (Theorem A). *For every γ in a generic subset of Γ_m , the set Λ of parameters λ such that $\gamma(\lambda)$ has (at least) one solenoidal attractor with bounded combinatorics on $(-1, 1)$ has zero Lebesgue measure.*

Proof. We divide the proof in several steps.

Step I (Marking restrictive intervals). It turns out that a multimodal map may have many disjoint cycles of restrictive intervals. To deal with that we need to "mark" one of those restrictive intervals. To this end fix $j \in \mathbb{N}^*$ and $q, n \in \mathbb{N} \setminus \{0, 1\}$. Let $\mathcal{O}_{j,q,n}$ be the set of all pairs (f_0, P_0) , such that

- A. The map $f_0 \in \Gamma$ has j critical points in $[-1, 1]$.
- B. P_0 is a restrictive interval of f_0 such that each $f_0^i(P_0)$ have at most one critical point for every i , $\cup_i f_0^i(P_0)$ contains n critical points and P_0 has a repelling periodic point in its boundary, with period $q' < q$. In particular $f_0^{q'}(\partial P_0) \subset \partial P_0$.
- C. The f_0 -forward orbit of any critical point on the orbit of such restrictive interval P_0 does not fall in the orbit of such periodic point.

Note that the image $\pi_1(\mathcal{O}_{j,q,n})$ of the projection onto the first coordinate in $\mathcal{O}_{j,q,n}$ is an open subset of Γ . Of course the countable family

$$\{\pi_1(\mathcal{O}_{j,q,n})\}_{j,q,n}$$

covers all infinitely renormalizable multimodal maps.

Fix $(f_0, P_0) \in \mathcal{O}_{j,q,n}$. By the implicit function theorem the repelling periodic point of f_0 in the boundary of P_0 has an analytic continuation that is also repelling and it defines a restrictive interval P_g for each map g in an open connected neighborhood \mathcal{V}_0 of f_0 on Γ and such restrictive interval also satisfies properties A., B. and C. In particular the family \mathcal{F} of pairs (\mathcal{V}, P) where

- 1. \mathcal{V} is an open and connected subset of Γ , with $f_0 \in \mathcal{V}$.
- 2. The real analytic function

$$g \in \mathcal{V} \mapsto P(g)$$

associate with each map $g \in \mathcal{V}$ a restrictive interval $P(g)$ of g satisfying $(g, P(g)) \in \mathcal{O}_{j,q,n}$ and moreover $P(f_0) = P_0$.

is non empty and consequently by Zorn's Lemma \mathcal{F} has a maximal element with respect to the order $(\mathcal{V}_1, P_1) < (\mathcal{V}_2, P_2)$ if and only if $\mathcal{V}_1 \subset \mathcal{V}_2$ and $P_2(g) = P_1(g)$ for every $g \in \mathcal{V}_1$. We claim that such maximal element is unique.

We claim that if $(\mathcal{V}_0, P_0), (\mathcal{V}_1, P_1) \in \mathcal{F}$ then $P_0 = P_1$ on $\mathcal{V}_0 \cap \mathcal{V}_1$. Indeed since $f \in \mathcal{V}_i$, $i = 0, 1$, has always j critical points (moving continously with respect to f , since they are quadratic) and a point $b_{f,i} \in \partial P_i(f)$ is a repelling periodic point of f that is analytic continuation of $b_{f_0,0} = b_{f_0,1}$, it follows that all those periodic points have exactly the same combinatorics with respect to the symbolic dynamics defined by partition induced by the critical points. In particular if $f \in \mathcal{V}_0 \cap \mathcal{V}_1$ then $b_{f,0}, b_{f,1}$ are repelling periodic points of f with the same combinatorics. Since f has negative schwarzian derivative, the minimal principle implies that $b_{f,0} = b_{f,1}$. This proves the claim.

In particular the maximal element of \mathcal{F} , denoted by $(\mathcal{V}_{f_0, P_0}, P_{f_0, P_0})$, can be described by

$$\mathcal{V}_{f_0, P_0} = \cup_{(\mathcal{V}, P) \in \mathcal{F}} \mathcal{V}$$

and $P_{f_0, P_0}(f) = P(f)$ for every $f \in \mathcal{V}$ satisfying $(\mathcal{V}, P) \in \mathcal{F}$. Note that

$$\mathcal{G} = \{\mathcal{V}_{f_0, P_0} : (f_0, P_0) \in \mathcal{O}_{j, q, n}\}$$

is a partition of $\mathcal{O}_{j, q, n}$. We claim that such partition has a countable number of elements. Indeed suppose that

$$\{(f_\lambda, P_\lambda)\}_{\lambda \in \Lambda}$$

is an uncountable family such that

$$\mathcal{V}_{f_\lambda, P_\lambda} \neq \mathcal{V}_{f_\mu, P_\mu}$$

for every $\lambda \neq \mu$. Choose a complex neighborhood W of $[-1, 1]$ such that $\overline{W} \subset U$. Then there exists a sequence $\lambda_k \in \Lambda$, $k \in \mathbb{N}$, such that

- P1. There are n and $q' < q$ such that $(f_{\lambda_k}, P_{\lambda_k})$ satisfies the conditions A and B for every k .
- P2. $\lim_k (f_{\lambda_k}, P_{\lambda_k}) = (f_\infty, P_\infty)$ on $\mathcal{B}_\mathbb{R}(W)$, where (f_∞, P_∞) is a multimodal map with j quadratic critical points, negative schwarzian derivative and $f_\infty(-1, 1) \subset (-1, 1)$, and that also satisfies A , B . and C . for the very same n and q' as in P1.
- P3. There is $\theta > 1$ such that if b_{λ_k} is the repelling periodic point in the boundary of P_{λ_k} then $|Df_{\lambda_k}^{q'}(b_{\lambda_k})| > \theta$ for every k .
- P4. If $k \neq k'$ then $\lambda_k \neq \lambda_{k'}$.

By the implicit function theorem there is a ball Y of $\mathcal{B}_\mathbb{R}(W)$ around f_∞ and a real-analytic function P defined in Y such that for every $f \in Y$ we have that $P(f)$ is a restrictive interval for f satisfying A and B , and additionally $P(f_{\lambda_k}) = P_{\lambda_k}$ for every large k . In particular, choose k_0, k_1 large enough and a small connected open subset $\tilde{W} \subset \Gamma$ around the segment $\{tf_{\lambda_{k_0}} + (1-t)f_{\lambda_{k_1}}, t \in [0, 1]\}$. Then the function P is defined in \tilde{W} , which implies that

$$\mathcal{V}_{f_{\lambda_{k_0}}, P_{\lambda_{k_0}}} = \mathcal{V}_{f_{\lambda_{k_1}}, P_{\lambda_{k_1}}},$$

which is a contradiction. This completes the proof of our claim.

Step II. (Replacing multimodal maps by extended maps of type n) A real analytic multimodal map does not have the nice structure of a multimodal map of type n . Fix some open set $\mathcal{V}_{f_0, P_0} \subset \mathcal{O}_{j, q, n}$. We will replace every $g \in \pi_1(\mathcal{V}_{f_0, P_0})$ by a induced map that is an extended map of type n . Denote by I_g the extended map of type n that is the renormalization of g associated with the restrictive interval $P_{f_0, P_0}(g)$. Of course I_g is a real-analytic extended map with negative schwarzian derivative and quadratic critical points.

Step III. (Complexification). Fix $p \geq 2$ Let $\mathcal{W} \subset \mathcal{B}_{nor}(U)$ be the domain of the complexification of the p -bounded renormalization operator \mathcal{R} as defined Section 3. Note that if I_g is infinitely renormalizable with p -bounded combinatorics we don't necessarily have that $I_g \in \mathcal{W}$. It may be the case that I_g is not defined on the domain U , for instance. However by the beau complex bounds given by Proposition 2 and the universality result in Proposition 4.6 there is k such that

$R^{k'}(I_g) \in \mathcal{W}$ for every $k' \geq k$. Again by the beau complex bounds and Proposition 4.6 we can find open subsets $\mathcal{V}_{f_0, P_0}^k \subset \mathcal{V}_{f_0, P_0}$ such that for

- E1. For every $g \in \mathcal{V}_{f_0, P_0}^k$ we have that $\mathcal{I}_k(g) = R^k(I_g)$ is well defined and it belongs to \mathcal{W} .
- E2. For every $g \in \mathcal{V}_{f_0, P_0}^k$ that is infinitely renormalizable with p -bounded combinatorics we have $R^{k'}(I_g) \in \mathcal{W}$ for every $k' \geq k$.
- E3. We have that

$$\cup_k \mathcal{V}_{f_0, P_0}^k$$

contains all infinitely maps in \mathcal{V}_{f_0, P_0} which are renormalizable with p -bounded combinatorics.

The operator \mathcal{I}_k has a complexification (it can be proven using *exactly* the same argument as in the complexification of the renormalization operator in Section 3). From now on we restrict \mathcal{I}_k to real maps. Note that the image of the operator $D_g \mathcal{I}_k$ is dense in $T\mathcal{B}_{nor}^{\mathbb{R}}(U)$ (again, the argument is the same as with the renormalization operator in Theorem 3).

Step IV. (Applying the hyperbolicity of $\Omega_{n,p}$). Due Theorem 5 we have that $\Omega_{n,p}$ is a hyperbolic invariant set of \mathcal{R} . Moreover Corollary 9.1 says that $W^s(\Omega_{n,p})$ has transversal empty interior. Theorem 3 tells us that $D_F \mathcal{R}(T_F \mathcal{B}_{nor}^{\mathbb{R}}(U))$ is dense in $T_{\mathcal{R}F} \mathcal{B}_{nor}^{\mathbb{R}}(U)$ for every $F \in \mathbb{R}^{\mathbb{R}}$. So we conclude that \mathcal{R} (restricted to real maps) satisfies the assumptions of Theorem 1 in [43] (taking $k = \omega_{\mathbb{R}}$ there). Now we can apply Proposition 8.1 of [43] taking $\mathcal{M} = \mathcal{I}_k$ to conclude that for a generic $\gamma \in \Gamma_n^{\omega_{\mathbb{R}}}(\mathcal{B}_{\mathbb{R}})$ the set of parameters $\lambda \in [-1, 1]^n$ where $\mathcal{I}_k(\gamma(\lambda))$ is infinitely renormalizable with p -bounded combinatorics has zero Lebesgue measure. Since there is just a countable number of choices for k , elements of \mathcal{G} , q , p and j , we concluded the proof. \square

Indeed Proposition 8.1 of [43] implies an analogous result for finitely differentiable families of maps in Γ . We refer the reader to [43] for additional statements and definitions for this setting.

10.2. Transversal families of polynomial-like maps. Recall the definition of \hat{E}_f^h and \hat{E}_f^v in Section 4.2.

Theorem 8 (Transversal families). *Let Λ be an open subset of \mathbb{C}^d . Let*

$$\lambda \in \Lambda \mapsto f_\lambda: V_\lambda^1 \rightarrow V_\lambda^2$$

be a complex analytic family of polynomial-like maps such that for every $\lambda \in \Lambda \cap \mathbb{R}^d$ we have that V_λ^1, V_λ^2 are symmetric with respect with \mathbb{R} , its real trace is an interval, $f_\lambda(x) \in \mathbb{R}$ for every $x \in \mathbb{R}$, f_λ has negative Schwarzian derivative and just quadratic critical points on the real line. Suppose that for every $\lambda_0 \in \mathbb{R}^d$ such that f_{λ_0} is infinitely renormalizable with bounded combinatorics we have that

(Transversality assumption.) *Every holomorphic vector in a neighborhood of $K(f_{\lambda_0})$ can be written as a sum of a vector in $\hat{E}_{f_{\lambda_0}}^h$ and a vector in*

$$D_\lambda f_\lambda|_{\lambda=\lambda_0}(\mathbb{R}^d).$$

Then the set of parameters $\lambda \in \Lambda \cap \mathbb{R}^d$ where f_λ is infinitely renormalizable with bounded combinatorics has zero d -dimensional Lebesgue measure.

Proof. We can find a countable family of domains $U_i \subset \mathbb{C}$, symmetric with respect to \mathbb{R} , and open subsets $\Lambda_i \subset \Lambda \cap \mathbb{R}^d$ such that $\cup_i \Lambda_i = \Lambda \cap \mathbb{R}^d$, $f_\lambda \in \mathcal{B}(U_i)$, for $\lambda \in \Lambda_i$, with $K(f_\lambda) \cap \mathbb{R} \subset U_i \cap \mathbb{R}$, and

$$\lambda \in \Lambda_i \mapsto f_\lambda \in \mathcal{B}(U_i)$$

is an real analytic family. It is enough to prove the conclusion of Theorem 8 for each one of those families. So fix i . The proof goes as the proof of Theorem 7. We can define the sets $\mathcal{O}_{j,q,n}$ replacing the pairs (f, P) by pairs of the form (λ, P) , where $\lambda \in \Lambda_i$ and P is a restrictive interval of f_λ . In a similar way we can define $(\mathcal{V}_{\lambda_0, P_{\lambda_0}}, P_{\lambda_0, P_{\lambda_0}})$, the sets $\mathcal{V}_{\lambda_0, P_{\lambda_0}}^k \subset \Lambda_i$ and the real-analytic parametrized families

$$\lambda \in \mathcal{V}_{\lambda_0, P_{\lambda_0}}^k \rightarrow \mathcal{I}_k(f_\lambda) \in \mathcal{W}.$$

Suppose that f_λ is infinitely renormalizable with p -bounded combinatorics. Then

$$D_{f_\lambda} \mathcal{I}_k(E_{f_\lambda}^h) \subset E_{\mathcal{I}_k(f_\lambda)}^h.$$

This follows exactly as the proof of Proposition 4.2. On the other hand we know (see the proof of Theorem 7) that $\text{Im } D_{f_\lambda} \mathcal{I}_k$ is dense in $T_{\mathcal{I}_k(f_\lambda)} \mathcal{B}_{nor}^{\mathbb{R}}(U)$. By the Transversality assumption this implies that there is a subspace $S_\lambda \subset \mathbb{R}^d$, with $\dim S_\lambda = n$, such that

$$D_{f_\lambda} \mathcal{I}_k \cdot D_\lambda f_\lambda(S_\lambda) \pitchfork E_{\mathcal{I}_k(f_\lambda)}^h.$$

Suppose that λ_0 is such that f_{λ_0} is infinitely renormalizable with p -bounded combinatorics. Let $v_1, \dots, v_n, v_{n+1}, \dots, v_d$ be a basis of \mathbb{R}^d such that v_1, \dots, v_n is a basis for S_{λ_0} . Then for every $\gamma = (\gamma_1, \dots, \gamma_{d-n}) \in \mathbb{R}^{n-d}$ that is small enough we have that the family

$$\theta = (\theta_1, \dots, \theta_n) \mapsto g_\theta = f_{\lambda_0 + \sum_{i=1}^n \theta_i v_i + \sum_{i=n+1}^d \gamma_{i-n} v_i},$$

where θ is also small, satisfies

$$D_{g_\theta} \mathcal{I}_k \cdot D_\theta g_\theta(\mathbb{R}^n) \pitchfork E_{\mathcal{I}_k(g_\theta)}^h.$$

So by [43, Corollary 10.2] we have that for every small γ , the set of small parameters θ such that g_θ is infinitely renormalizable with bounded combinatorics has zero n -dimensional Lebesgue measure. By the Fubini's Theorem it follows that in a small neighborhood the parameter λ_0 the set of parameters λ such that f_λ is infinitely renormalizable with p -bounded combinatorics has zero d -dimensional Lebesgue measure. This completes the proof. \square

Proof of Theorem C. Let $f_{\lambda_1, \lambda_2}(z) = z^3 - 3\lambda_1^2 z + \lambda_2$. Note that if $\lambda_1 = 0$ then f_{λ_1, λ_2} is not infinitely renormalizable, so we assume that $\lambda_1 \neq 0$. Let $\lambda_0 = (a, b)$, $a \neq 0$. Then

$$\partial_\lambda f_\lambda|_{\lambda=\lambda_0}(\mathbb{R}^2) = \{cz + d, \ c, d \in \mathbb{R}\}$$

By Proposition 4.8 we have that $\hat{E}_{f_\lambda}^v$ is the space of cubic polynomials, so $\dim \hat{E}_{f_\lambda}^v = 4$ and

$$\partial_\lambda f_\lambda|_{\lambda=\lambda_0}(\mathbb{R}^2) \subset \hat{E}_{f_\lambda}^v.$$

We claim that

$$(117) \quad \{2z^3 - b, -3z^2 - 3a^2 - 1\} \subset \hat{E}_{f_\lambda}^h \cap \hat{E}_{f_\lambda}^v$$

Indeed, let $H_t(z) = z/t$. Then

$$2z^3 - b = \partial_t(H_t \circ f_{a,b} \circ H_t^{-1}(z))|_{t=1},$$

so $2z^3 - b = \alpha_1(f_{a,b}(z)) - Df_{a,b}(z)\alpha_1(z)$, where $\alpha_1(z) = \partial_t H_t(z)|_{t=1} = -z$. Let $S_t(z) = z - t$. Then

$$3z^2 - 3a^2 - 1 = \partial_t(S_t \circ f_{a,b} \circ S_t^{-1}(z))|_{t=0},$$

so $3z^2 - 3a^2 - 1 = \alpha_2(f_{a,b}(z)) - Df_{a,b}(z)\alpha_2(z)$, where $\alpha_2(z) = \partial_t S_t(z)|_{t=0} = -1$. Since $\{1, z, 2z^3 - b, 3z^2 - 3a^2 - 1\}$ is a basis of $\hat{E}_{f_\lambda}^v$, by (27) and (117) we have that every holomorphic vector in a neighborhood of $K(f_{a,b})$ can be written as a sum of a vector in $\hat{E}_{f_{a,b}}^h$ and a vector in $\partial_\lambda f_\lambda|_{\lambda=\lambda_0}(\mathbb{R}^2)$. Now we apply Theorem 8. \square

10.3. Compositions of quadratic maps. We can say something about a specific family of extended maps of type n . This family was introduced in [40]. Let $\lambda = (\lambda_i)_{i \leq n}$, with $\lambda_i \in [0, 1]$ and define

$$F_\lambda: \mathbb{C} \times \{i\}_{i \leq n} \rightarrow \mathbb{C} \times \{i\}_{i \leq n}$$

as $F_\lambda(z, i) = (-2\lambda_i z^2 + 2\lambda_i - 1, i + 1 \bmod n)$.

It follows from the study in [40] that each possible combinatorial type of an infinitely renormalizable extended map of type n with combinatorics bounded by p can be realized by a unique parameter in $[0, 1]^n$ and the set of such parameters $\Lambda_{p,n} \subset [0, 1]^n$ is a Cantor set [40, Theorem 2]. The following result answers a conjecture in [40].

Theorem 9. *We have that $m(\Lambda_{p,n}) = 0$, where m is the n -dimensional Lebesgue measure.*

Proof. Due Corollary 10.2 in [43], it is enough to show that this family is transversal to the horizontal distribution $F \rightarrow E_F^h$. We will give a proof similar to the proof of the transversality of the quadratic family by Lyubich [27]. Indeed, suppose by contradiction that there exists $\lambda_0 \in \Lambda_{p,n}$ and $w \in \mathbb{R}^n \setminus \{0\}$ such that

$$v = \partial_\lambda F_\lambda|_{\lambda=\lambda_0} \cdot w \in E_{F_{\lambda_0}}^h.$$

So there is a quasiconformal vector field α_0 , defined in a neighborhood of the post-critical set $P(F_{\lambda_0})$ satisfying (17) on $P(F_{\lambda_0})$. Since this is a family of polynomials, the conformal dynamics outside the Julia set of F_{λ_0} is always the same, so v is also a *vertical* direction, that is, there exists a conformal vector field α_1 defined outside the Julia set such that (17) holds outside the Julia set. Using the infinitesimal pull-back argument we can find a quasiconformal vector field solution α that satisfies (17) everywhere and moreover it is conformal outside the Julia set. Since F_{λ_0} does not support invariant line fields on its Julia set we conclude that α is conformal everywhere and indeed it is equal to zero, since it is zero at three points of $\overline{\mathbb{C}} \times \{i\}$, for each $i \leq n$. So $v = 0$, which implies $w = 0$. \square

Remark 10.1. *Note that $\Lambda_{p,n}$ only includes the parameters where each renormalization involves all n critical points, that is, each cycle of intervals covers all critical points. If we consider infinitely renormalizable maps where fewer points are involved then the set of parameters it is not a Cantor set anymore. However it is likely that this larger subset of parameters also have zero Lebesgue measure.*

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