Singular Perturbations in the Quadratic Family with Multiple Poles

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Abstract

We consider the quadratic family of complex maps given by \( q_c(z) = z^2 + c \) where \( c \) is the center of a hyperbolic component in the Mandelbrot set. Then, we introduce a singular perturbation on the corresponding bounded superattracting cycle by adding one pole to each point in the cycle. When \( c = -1 \) the Julia set of \( q_{-1} \) is the well known basilica and the perturbed map is given by \( f_\lambda(z) = z^2 - 1 + \lambda/(z^{d_0}(z + 1)^{d_1}) \) where \( d_0, d_1 \geq 1 \) are integers, and \( \lambda \) is a complex parameter such that \(|\lambda|\) is very small. We focus on the topological characteristics of the Julia and Fatou sets of \( f_\lambda \) that arise when the parameter \( \lambda \) becomes nonzero. We give sufficient conditions on the order of the poles so that for small \( \lambda \) the Julia sets consist of the union of homeomorphic copies of the unperturbed Julia set, countably many Cantor sets of concentric closed curves, and Cantor sets of point components that accumulate on them.
1 Introduction

In the last decade a number of papers have appeared that deal with rational maps obtained by perturbing a complex polynomial by adding a pole at some point in the Fatou set of the polynomial. This kind of perturbation of a polynomial is usually called a singular perturbation since the degree of the resulting rational map increases when the pole is added. As a consequence of this perturbation the structure of the Julia sets often change dramatically after the addition of the pole since new critical points appear close to the pole.

The most studied case is the singular perturbation of the polynomial \( z^n \) with \( n \geq 2 \) obtained by adding a pole at the origin. In this case the corresponding rational map is given by \( z^n + \lambda/z^d \) where \( d \geq 1 \). See, for example, [4, 5, 6, 7]. For the unperturbed map (that is, when \( \lambda = 0 \)) the Julia set is the unit circle. Points with modulus larger than one are attracted to the superattracting fixed point at infinity, while points with modulus smaller than one are attracted to the superattracting fixed point at the origin. When \( \lambda \neq 0 \) the superattracting fixed point at the origin is replaced by a pole. However, the rational map \( z^n + \lambda/z^d \) inherits some properties of the polynomial. For example, infinity is still a superattracting fixed point. Since the origin is a pole of order \( d \), there is an open neighborhood of 0 that is mapped onto a neighborhood of \( \infty \) in a \( d \)-to-\( -1 \) fashion. If the component of the basin of \( \infty \) which contains \( \infty \) is disjoint from this neighborhood around the origin we call this set the trap door, since any orbit that eventually enters the immediate basin of attraction of infinity must pass through the trap door at some iterate.

The first appearance of this type of singular perturbation was in 1988 ([12]) when McMullen used some members of this family as an example of a rational map whose Julia set is a Cantor set of simple closed curves. More precisely, McMullen showed that if the arithmetic condition \( 1/n + 1/d < 1 \) is satisfied then, for \( \lambda \) sufficiently small, the critical values of \( z^n + \lambda/z^d \) belong to the trap door and the Julia set of the map is a Cantor set of simple closed curves. When this arithmetic condition is not satisfied, it is not possible to control the behavior of the critical points. In particular in any neighborhood of \( \lambda = 0 \) there are infinitely many parameter values for which the associated Julia set is a Sierpiński curve. If parameter values are drawn from Sierpiński holes of different escape time, then the dynamics of the corresponding maps on their respective Sierpiński curve Julia sets are known to be dynamically different ([3]).

Another family of perturbed polynomials of recent interest is of the form \( z^n + c + \lambda/z^d \) where \( c \) is chosen to be the center of a hyperbolic component of the corresponding Multibrot set and \( \lambda \) is chosen to be small ([1, 12]). In [9] the case when the function \( z^n \) is perturbed with 2 poles is studied. In [10] the quadratic function \( z^2 + c \) is perturbed with a pole at the origin in the case when \( c \) belongs to a hyperbolic component of the Mandelbrot set but is not at the center.

In this article we consider a different case of singular perturbations to the quadratic polynomial \( z^2 + c \) with multiple poles. We focus on the case when \( c \) lies at the center of a hyperbolic component of the Mandelbrot set and where the perturbation consists of the addition of multiple poles in place of its bounded superattracting cycle.
In general, if $c$ is the center of a hyperbolic component of the Mandelbrot set such that the critical point 0 is in a cycle of period $N > 1$ given by $p_0 = 0, p_1 = f(p_0) = c, ..., p_{N-1} = f(p_{N-2}), f(p_{N-1}) = p_0 = 0$, the function is given by

$$f_\lambda(z) = z^2 + c + \frac{\lambda}{\prod_{i=0}^{N-1}(z - p_i)^{d_i}}.$$  

That is, we add a pole at each one of the points in the superattracting $N$–cycle. When $\lambda = 0$ we have the quadratic map. When $\lambda$ becomes nonzero the degree of the map changes from 2 to $2 + d_0 + d_1 + \ldots + d_{N-1}$ and new critical points are created. When $\lambda$ is very small the map behaves like the quadratic family for $z$ values outside small neighborhoods of the poles. For example, the point at infinity is still a superattracting fixed point and it has an immediate basin of attraction denoted $B_\lambda$. There are $N$ disjoint open neighborhoods of the poles that are simply connected preimages of the immediate basin of attraction of infinity. These sets are the trap doors denoted by $T_i = T_i(\lambda)$ for $i = 0, ..., N - 1$. If a point has an orbit that is attracted to infinity and the point is not in the immediate basin of attraction of infinity then its orbit must escape through one of the trap doors. We will show that there are a number of critical points surrounding each one of the poles that are mapped close to the next point in the cycle. When $\lambda$ is small and for suitable choices of the order of the poles $d_i$, all these critical points are mapped inside the trap doors and escape to infinity. In these cases we know the fate of every critical point and this allows us to study the topological characteristics of the Julia sets of $f_\lambda$.

The Fatou set of $f_\lambda$, denoted by $F(f_\lambda)$, is defined to be the set of points at which the family of iterates of $f_\lambda$ is a normal family in the sense of Montel. The complement of the Fatou set in the Riemann sphere is the Julia set of $f_\lambda$ and is denoted by $J(f_\lambda)$. By definition, the Fatou set is open and the the Julia set is closed. The Julia set is also the closure of the set of repelling periodic points of $f_\lambda$ and it is the set where $f_\lambda$ has sensitive dependence on initial conditions. Both sets, $F(f_\lambda)$ and $J(f_\lambda)$, are completely invariant. In this paper we study the topological properties of the Julia and Fatou sets of $f_\lambda$ and dynamics of $f_\lambda$ restricted to these sets.

Figures 1-2 display the Julia set of $f_\lambda$ for particular values of the parameters. Figure 1 shows the Julia set corresponding to the parameter $c = -1$ which is the center of the period two hyperbolic component of the Mandelbrot set. When $\lambda = 0$ the Julia set of $f_0(z) = z^2 - 1$ is the well known basilica which has a superattracting cycle of period two at $p_0 = 0$ and $p_1 = -1$. When $\lambda \neq 0$ the perturbed basilica is given by $f_\lambda(z) = z^2 - 1 + \lambda/(z^{d_0}(z + 1)^{d_1})$. Figure 2 shows the Julia set corresponding with the parameter $c = c_r \approx -0.12256 + 0.74486i$, i.e., $c_r$ is defined to be the center of the hyperbolic component of period three in the portion of the Mandelbrot set that lies in the upper half plane. When $\lambda = 0$ the Julia set of $f_0(z) = z^2 + c_r$ is the well known Douady rabbit which has a superattracting cycle of period three at $p_0 = 0, p_1 = c_r$, and $p_2 = c_r^2 + c_r$. When $\lambda \neq 0$ the perturbed Douady rabbit is given by $f_\lambda(z) = z^2 + c_r + \lambda/(z^{a_0}(z - c_r)^{a_1}(z - c_r^2 - c_r)^{b_2}).$
The perturbation when \( \lambda \) becomes nonzero happens far away from the immediate basin of attraction of infinity and inside the bulbs of the Julia set for the unperturbed map. It is possible to find \( \delta > 0 \) such that for \( |\lambda| < \delta \) the boundary of \( B_\lambda \) is homeomorphic to the Julia set of \( f_0 \). This fact was shown in the case of a single pole perturbation in [1] using quasiconformal surgery. The same proof works well for \( f_\lambda \) but in this paper we present a different proof that uses holomorphic motions.

**Theorem A (The Boundary of \( B_\lambda \)).** There exists \( \delta > 0 \) such that, if \( |\lambda| < \delta \), the boundary of \( B_\lambda \) is homeomorphic to \( \partial B_0 = J(f_0) \) and \( f_\lambda \) restricted to \( \partial B_\lambda \) is conjugate to \( f_0 \) on \( J(f_0) \).

By this result the structure of the Julia set of \( f_0 \) persists in \( f_\lambda \) as \( \partial B_\lambda \) when \( \lambda \) is small. However, the structure of \( J(f_\lambda) \) inside the bounded components of \( \partial B_\lambda \) is far more complex. In Figure 1, note that the boundary of \( B_\lambda \) looks very similar to the basilica and in Figure 2 that the boundary of \( B_\lambda \) is difficult to distinguish from the Douady rabbit. Figure 3 shows a magnification of the Julia set (for the basilica parameter \( c = -1 \)) of \( f_{10-22} \) near the two poles at \( p_0 = 0 \) and \( p_1 = -1 \). The two trap doors: \( T_0 \) containing the origin and \( T_1 \) containing -1, are visible in these plots. Also note doubly connected components of the Fatou set.

For sufficiently small values of \( \lambda \) and under a certain arithmetic condition concerning the order of the poles, we can describe the topological structure and the dynamics on the Julia and Fatou sets of \( f_\lambda \).

Recall that \( p_i \) is a pole of \( f_\lambda \) of order \( d_i \) for every \( 0 \leq i \leq N - 1 \), with \( p_0 = 0, p_1 = f_0(0), \ldots, p_i = f_i(0) \).

**Definition 1.1.** The natural numbers \( d_0, d_1, \ldots, d_{N-1} \) satisfy the arithmetic condition \( I \) when \( 2d_1 > d_0 + 2 \) and \( d_{i+1} > d_i + 1 \) for every \( 1 \leq i \leq N - 1 \).

**Theorem B (Structure of the Fatou set).** Suppose that \( |\lambda| \) is sufficiently small and the natural numbers \( d_0, d_1, \ldots, d_{N-1} \) satisfy the arithmetic condition \( I \). Then all the free critical orbits of \( f_\lambda \) escape to \( \infty \) but the critical points themselves do not lie in \( B_\lambda \). The Fatou set contains countably many simply connected components and annuli.

**Theorem C (Structure of the Julia set).** Suppose that \( |\lambda| \) is sufficiently small and the natural numbers \( d_0, d_1, \ldots, d_{N-1} \) satisfy the arithmetic condition \( I \). Then the Julia set contains countably many preimages of the boundary of \( B_\lambda \), a countable collection of Cantor sets of closed curves, and an uncountable number of point components that accumulate on these curves.

We will see from the proofs of Theorems B and C that we have more information about the Fatou and the Julia set. For instance, from the proof of Theorem B, we will know exactly which components of the Fatou set are simply connected (disks) and which components are doubly connected (annuli). In the same way, from the proof of Theorem C, we will understand the dynamics of \( f_\lambda \) restricted to its Julia set.
The paper is organized in the following manner. In §2 we approximate the location of the critical points and critical values of $f_\lambda$. In §3 we prove Theorem A using a holomorphic motion of $J(f_0)$. In §4 we study the topology of $F(f_\lambda)$ proving Theorem B and in §5 we investigate the topological structure and dynamics on $J(f_\lambda)$ proving Theorem C. In §6 we illustrate our results in detail for the example of the basilica where $c = -1$, $d_0 = 7$ and $d_1 = 5$.

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2 Preliminaries

In this section we compute the number, location, and approximate values of the critical points and critical values of $f_\lambda$ (see Eq. 1.1).

Notice that when $\lambda \neq 0$, $f_\lambda$ has degree $2 + d_0 + d_1 + \ldots + d_{N-1}$ and so it has $2 + 2(d_0 + d_1 + \ldots + d_{N-1})$ critical points counting multiplicities. Infinity is a critical point of order 1 and the poles located at $p_i$ are critical points of order $d_i - 1$. That is a total of $d_0 + d_1 + \ldots + d_{N-1} - N + 1$ critical points that are preimages of infinity. The fate of the
Figure 2: Dynamical planes of \( f_\lambda(z) = z^2 + c_r + \lambda/(z^{11}(z-c_r)^7(z-c_r^2-c_r)^9) \) for two different values of \( \lambda \).

other \( d_0 + d_1 + \ldots + d_{N-1} + N + 1 \) “free” critical points determine the topology and the dynamics of the Julia set of \( f_\lambda \).

Since the map \( f_\lambda \) is a singular perturbation of the quadratic map \( z^2 + c \), these \( 1 + d_0 + d_1 + \ldots + d_{N-1} + N \) critical points of \( f_\lambda \) are located close to the poles for sufficiently small values of the parameter \( \lambda \). We denote by \( C_i \) the set of critical points of \( f_\lambda \) close to \( p_i \). More precisely, we define \( \begin{align*}
C_i &= \{ c_\lambda \mid c_\lambda \neq p_i \text{ is a critical point of } f_\lambda \text{ and } c_\lambda \to p_i \text{ as } \lambda \to 0 \}
\end{align*} \)
for every value \( 0 \leq i \leq N-1 \). The next lemma gives a precise description of the critical points and the critical values of \( f_\lambda \) when \( \lambda \) is small.

We write \( f(\lambda) = g(\lambda) + o(h(\lambda)) \) as \( \lambda \to 0 \) if and only if \( \lim_{\lambda \to 0} \frac{f(\lambda) - g(\lambda)}{h(\lambda)} = 0 \), and we write \( f(\lambda) = g(\lambda) + O(h(\lambda)) \) as \( \lambda \to 0 \) if and only if \( \limsup_{\lambda \to 0} \left| \frac{f(\lambda) - g(\lambda)}{h(\lambda)} \right| < \infty \).

Lemma 2.1. Let \( \lambda \) be sufficiently small. The following statements hold:

(a) \( f_\lambda \) has \( d_0+2 \) critical points in \( C_0 \) approximately symmetrically distributed around \( p_0 = 0 \).

Moreover, if \( c_\lambda \in C_0 \) there exists \( k_0 \neq 0 \) such that \( c_\lambda = k_0 \lambda^{\frac{1}{\nu_0}} + o\left( \lambda^{\frac{1}{\nu_0}} \right) \) and \( f_\lambda(c_\lambda) = p_1 + O\left( \lambda^{\frac{2}{\nu_0}} \right) \).

(b) \( f_\lambda \) has \( d_i + 1 \) critical points in \( C_i \) approximately symmetrically distributed around \( p_i \).
Moreover, if \( c_\lambda \in C_i \) there exists \( k_i \neq 0 \) such that 
\[
c_\lambda = p_i + k_i \lambda^{\frac{1}{d_i+1}} + o \left( \lambda^{\frac{1}{d_i+1}} \right)
\]
and 
\[
f_\lambda(c_\lambda) = p_{i+1} + o \left( \lambda^{\frac{1}{d_{i+1}} \lambda^{\frac{1}{d_{i+1}}} \right),
\]
for every \( 1 \leq i \leq N-1 \).

**Proof.** A simple calculation shows that the critical points of \( f_\lambda \) satisfy

\[
2z^{d_0+2} \prod_{i=1}^{N-1} (z-p_i)^{d_i+1} = \lambda \left( \sum_{i=0}^{N-1} d_i \prod_{k=0,k\neq i}^{N-1} (z-p_k) \right).
\]

When \( \lambda = 0 \) this equation has \( d_0 + d_1 + \ldots + d_{N-1} + N + 1 \) solutions, the origin with multiplicity \( d_0 + 2 \) and \( p_i \) with multiplicity \( d_i + 1 \) for every \( 1 \leq i \leq N - 1 \). By continuity, for small enough values of \(|\lambda|\), the \( d_0 + d_1 + \ldots + d_{N-1} + N + 1 \) solutions to Eq. 2.1 become simple zeros of \( f_\lambda' \) that are approximately symmetrically distributed around the origin and the rest of the poles. As a consequence, when \(|\lambda|\) is small, \( d_0 + 2 \) of the critical points of \( f_\lambda \) are grouped around \( p_0 = 0 \), near the pole at the origin, while \( d_i + 1 \) of the critical points are grouped around the pole \( p_i \) for every \( 1 \leq i \leq N - 1 \).

First we compute an approximation of the critical points near 0. We observe that solving Eq. (2.1) is equivalent to solving \( T(z) = z \), where \( T(z) \) is defined by

\[
T(z) = \left( \lambda \frac{\sum_{i=0}^{N-1} d_i \prod_{k=0,k\neq i}^{N-1} (z-p_k)^{d_i+1}}{2 \prod_{i=1}^{N-1} (z-p_i)^{d_i+1}} \right)^{1/(d_0+2)} = \lambda^{\frac{1}{d_0+2}} R(z).
\]

In the above expression we introduce the auxiliary function \( R(z) \) and we observe that \( R(z) \) does not depend on the variable \( \lambda \). We also remark that there are \( d_0 + 2 \) possible different choices for the function \( T \) that are the \( (d_0 + 2) \) branches of the map given by Eq. (2.1).

Starting with the initial point 0 we find an approximate value, denoted by \( \tilde{c}_\lambda \), of the critical point near the origin given by

\[
\tilde{c}_\lambda = T(0) = k_0 \lambda^{\frac{1}{d_0+2}}, \quad \text{where } k_0 = \left( \frac{d_0}{2 \prod_{i=1}^{N-1} (-p_i)^{d_i}} \right)^{1/(d_0+2)}.
\]

From the above expression, it is clear that the values of \( \tilde{c}_\lambda \) form the vertices of a regular polygon with \( d_0 + 2 \) sides centered at the origin. Since the critical point \( c_\lambda \) is a fixed point of the function \( T \) we can obtain an upper bound for the distance between the critical point \( c_\lambda \) and the approximate value \( \tilde{c}_\lambda \). We have

\[
|c_\lambda - \tilde{c}_\lambda| = |T(c_\lambda) - T(0)| \leq |T'(\xi)||c_\lambda - 0| = |\lambda|^{\frac{1}{d_0+2}}|R'(\xi)||c_\lambda|,
\]

where \( \xi \) is a complex point in the segment joining the origin and \( c_\lambda \). From the above expression we finally have that

\[
\lim_{\lambda \to 0} \left| \frac{c_\lambda - \tilde{c}_\lambda}{\lambda^{\frac{1}{d_0+2}}} \right| \leq \lim_{\lambda \to 0} |R'(\xi)| \cdot |c_\lambda| = 0.
\]
This proves that \( c_\lambda = k_0 \lambda^{\frac{1}{\nu_0 + 2}} + o(\lambda^{\frac{1}{\nu_0 + 2}}) \).

In the same way, we can compute an approximation of the critical points near the pole \( p_i \), or in other words, in \( C_i \). In this case solving Eq. (2.1) is equivalent to solving the equation \( T(z) = z \) where

\[
T(z) = p_i + \left( \frac{\lambda}{2z^{d_0+2}} \prod_{k=1,k\neq i}^{N-1} (z - p_k)^{d_k+1} \right)^{1/(d_i+1)} = p_i + \lambda^{\frac{1}{d_i+1}} R(z).
\]

In this case taking the initial value \( T(p_i) \) we obtain an approximation of the critical points near \( p_i \),

\[
\tilde{c}_\lambda = T(p_i) = p_i + k_i \lambda^{\frac{1}{d_i+1}}, \quad \text{where} \quad k_i = \left( \frac{d_i}{2p_i^{d_0+1} \prod_{k=1,k\neq i}^{N-1} (p_i - p_k)^{d_k}} \right)^{\frac{1}{d_i+1}}.
\]

As before we can compute the distance between the critical point and its approximation

\[
|c_\lambda - \tilde{c}_\lambda| = |T(c_\lambda) - T(p_i)| \leq |T'(\xi)||c_\lambda - p_i| = |\lambda^{\frac{1}{d_i+1}} R'(\xi)||c_\lambda - p_i|,
\]

obtaining that \( c_\lambda = \tilde{c}_\lambda + o(\lambda^{\frac{1}{d_i+1}}) \).

Now, we turn our attention to critical values \( v_\lambda = f_\lambda(c_\lambda) \). Let \( c = c_\lambda \) be one of the \( d_0 + d_1 + \ldots + d_{N-1} + N + 1 \) critical points of \( f_\lambda \) given by Eq. (2.1), we can rewrite this equation as

\[
\frac{\lambda}{\prod_{i=0}^{N-1} (z - p_i)^{d_i}} = \frac{2z \prod_{i=0}^{N-1} (z - p_i)}{\sum_{i=0}^{N-1} d_i \prod_{k=0,k\neq i}^{N-1} (z - p_k)} = \frac{2z}{\sum_{i=0}^{N-1} d_i / (z - p_i)},
\]

and then replace \( z \) by \( c_\lambda \). Then the critical value \( v_\lambda = f_\lambda(c_\lambda) \) corresponding to \( c_\lambda \) is given by

\[
(2.2) \quad v_\lambda = f_\lambda(c) = c_\lambda^2 - c + \frac{\lambda}{\prod_{i=0}^{N-1} (c_\lambda - p_i)^{d_i}} = c_\lambda^2 + c + \frac{2c_\lambda}{\sum_{i=0}^{N-1} d_i / (c_\lambda - p_i)}.
\]

Then, we can compute an approximation for the critical values \( v_\lambda \) that we denote \( \tilde{v}_\lambda \). As before we start with the critical points close to zero. For \( c_\lambda \in C_0 \), we have that \( \tilde{c}_\lambda = k_0 \lambda^{\frac{1}{\nu_0 + 2}} \). Introducing this expression of \( \tilde{c}_\lambda \) in Eq. (2.2) we obtain

\[
\tilde{v}_\lambda = p_1 + k_0^2 \lambda^{\frac{2}{\nu_0 + 2}} + \frac{2k_0 \lambda^{\frac{2}{\nu_0 + 2}}}{d_0 / k_0 + \lambda^{\frac{2}{\nu_0 + 2}} \sum_{i=1}^{N-1} d_i / k_0 \lambda^{\frac{2}{\nu_0 + 2}} - p_1}.
\]

Hence \( \lim_{\lambda \to 0} \left| \frac{\tilde{v}_\lambda - p_1}{\lambda^{\frac{2}{\nu_0 + 2}}} \right| = |k_0|^2 (d_0 + 2) / d_0 \).

In the same way we obtain the corresponding result for \( c_\lambda \in C_i \), using the approximation, \( \tilde{c}_\lambda = k_i \lambda^{\frac{1}{d_i+1}} \), for \( 1 \leq i \leq N - 1 \).
Figure 3: Dynamical plane of \( f_\lambda(z) = z^2 - 1 + 10^{-22}/(z^7(z + 1)^5) \) near the two trap doors.

3 The immediate basin of attraction of infinity

In this section we prove that, for \(|\lambda|\) sufficiently small, the boundary of \( B_\lambda \) is a homeomorphic copy of the Julia set of \( f_0 \), i.e., the quadratic polynomial without the singular perturbation.

As is well known, there is a Böttcher coordinate \( \varphi_\lambda \) defined in a neighborhood of \( \infty \) in \( B_\lambda \) that conjugates \( f_\lambda \) to \( z \mapsto z^2 \) in a neighborhood of \( \infty \). If none of the free critical points lie in \( B_\lambda \), then it is well known that we may extend \( \varphi_\lambda \) so that it takes the entire immediate basin univalently onto \( \mathbb{C} \setminus \overline{D}^1 \) and hence conjugates \( f_\lambda \) to \( z \mapsto z^2 \) on all \( B_\lambda \). The following proposition shows that this occurs.

**Proposition 3.1.** If \(|\lambda|\) is sufficiently small, then the trap doors \( T_i(\lambda) \) for \( i = 0, \ldots, N - 1 \) are disjoint from \( B_\lambda \). Also, none of the free critical points lie in \( B_\lambda \).

**Proof.** Recall that the superattracting periodic orbit for \( f_0 \) is given by \( p_0 = 0, p_1 = c, p_2, \ldots, p_{N-1} \) where \( f_0(p_{N-1}) = 0 \). Let \( U_i \) denote the component of the interior of \( K(f_0) \), the unperturbed filled Julia set, that contains \( p_i \) and \( \gamma_i \) the boundary of \( U_i \), for \( i = 0, \ldots, N - 1 \). We have that \( f_\lambda^N \) preserves \( \gamma_i \) and is hyperbolic on this set since the critical orbit is periodic and hence bounded away from this set. There is an open annulus, \( A_i \), containing \( \gamma_i \) such that \( f_\lambda^N(A_i) \) is also an annulus and \( A_i \subset f_\lambda^N(A_i) \). Similarly, provided \(|\lambda|\) is sufficiently small, the larger annulus, \( f_\lambda^N(A_i) \), is mapped completely over itself by \( f_\lambda^N \). Hence \( B_\lambda \) cannot extend into the disk that is the bounded component of the complement of this annulus. Since the

\[1\text{We use } \overline{D} \text{ to denote the closure of the unit disk in } \mathbb{C}.\]
free critical points near \( p_i \) tend to \( p_i \) as \( \lambda \) tends to 0, this annulus may be chosen so that all the critical points near to \( p_i \) lie in this internal disk. Hence they do not lie in \( B_\lambda \).

The idea of the proof of Theorem A is the following. For \( \lambda \) sufficiently small, we can define a holomorphic motion of \( B_0 \) parameterized by \( \lambda \), obtaining \( B_\lambda \) as a result of this movement. Applying the \( \Lambda - \text{Lemma} \), established by Mañé, Sad and Sullivan ([8]), we extend this holomorphic motion to the closure of \( B_0 \). This will establish that the boundary of \( B_\lambda \) is a holomorphic motion of the boundary of \( B_0 \) which is equal to the Julia set of \( f_0 \). First recall the definition of a holomorphic motion and the \( \Lambda - \text{Lemma} \) ([8]).

**Definition.**

Let \( X \subset \hat{\mathbb{C}} \). We say that a map

\[
H : X \times \mathbb{D} \to \hat{\mathbb{C}} \\
(z, \lambda) \to H(z, \lambda)
\]

is a holomorphic motion of \( X \) parameterized by \( \mathbb{D} \) if

a) \( H(z, 0) = z \) for all \( z \in X \).

b) the map \( H(\cdot, \lambda) : X \to \hat{\mathbb{C}} \) is injective, for all \( \lambda \in \mathbb{D} \).

c) the map \( H(z, \cdot) : \mathbb{D} \to \hat{\mathbb{C}} \) is holomorphic, for all \( z \in X \).

**\( \Lambda \)-Lemma.** Let \( H : X \times \mathbb{D} \to \hat{\mathbb{C}} \) be a holomorphic motion. Then, \( H \) is continuous, and it extends to a unique holomorphic motion \( \bar{H} : \bar{X} \times \mathbb{D} \to \hat{\mathbb{C}} \), where \( \bar{X} \) is the closure of \( X \).

Suppose \( |\lambda| \) is chosen small enough so that Proposition 3.1 is satisfied and let \( \delta > 0 \) such that the Böttcher map \( \varphi_\lambda \) extends to the whole immediate basin of attraction \( B_\lambda \) for all \( |\lambda| < \delta \). Let \( \mathbb{D}_\delta \) denote the set of complex parameters \( \lambda \) with modulus smaller than \( \delta \). We can define now a holomorphic motion of \( B_0 \). More precisely, consider the following map:

\[
H : B_0 \times \mathbb{D}_\delta \to \hat{\mathbb{C}} \\
(z, \lambda) \to \varphi_\lambda^{-1} \circ \varphi_0(z).
\]

Next we verify that \( H \) is a holomorphic motion. By construction, we have that \( H(z, 0) = \varphi_0^{-1} \circ \varphi_0(z) = z \). If we fix the parameter \( \lambda \) we can see that the map \( H(\cdot, \lambda) \) is injective. This is immediate since the Böttcher mapping \( \varphi_\lambda \) is conformal. Finally, if we fix a point \( z \in B_0 \) we can see that \( H(z, \cdot) : \mathbb{D} \to \hat{\mathbb{C}} \) is a holomorphic map. In this case this map is a composition of holomorphic maps, since the Böttcher map depends analytically on parameters.

Geometrically, if we fix \( \lambda \in \mathbb{D} \), the map \( z \to H(z, \lambda) \) sends points in \( B_0 \) to points in \( B_\lambda \) according to the Böttcher coordinates (see Figure 4).

Finally, applying the \( \Lambda \)-Lemma to \( H \), we obtain a new holomorphic motion \( \bar{H} : \bar{B}_0 \times \mathbb{D} \to \hat{\mathbb{C}} \). Hence, it follows that the boundary of \( B_\lambda \) is the continuous image under \( \bar{H} \) of the Julia set of \( f_0 \). Finally, interchanging the role of 0 and \( \lambda \) we obtain that \( \bar{H} \) is a homeomorphism. This concludes the proof of Theorem A.
Figure 4: Sketch of the Holomorphic motion $H$. Geometrically, $H$ sends equipotentials and rays from $B_0$ to $B_\lambda$ according to Böttcher coordinates.

4 The Fatou set

In this section we will prove Theorem B that establishes the main properties of the Fatou set of $f_\lambda$ for small enough values of the parameter $\lambda$ where arithmetic condition $\mathcal{I}$ is satisfied.

**Lemma 4.1.** For $\lambda$ sufficiently small and $d_0, d_1, \ldots, d_{N-1}$ satisfying arithmetic condition $\mathcal{I}$, the critical points in $C_i$ are mapped inside the trap doors $T_{i+1}$, for $i = 0, \ldots, N - 1$, and escape to infinity.

**Proof.** Let $c = c_\lambda$ be one of the $d_0 + d_1 + \ldots + d_{N-1} + N + 1$ critical points of $f_\lambda$. Then the critical value $v_\lambda$ corresponding to $c_\lambda$ from equation 2.2 is given by

$$v_\lambda = c_\lambda^2 + c + \frac{2c_\lambda}{\sum_{i=0}^{N-1} \frac{d_i}{c_\lambda - p_i}}.$$

From the above expression it follows that, as $\lambda \to 0$, if $c_\lambda \to p_i$, then the corresponding critical value $v_\lambda \to p_{i+1}$, since $p_{i+1} = p_i^2 + c$. Hence, critical values corresponding to critical points in $C_0$, are close to $p_1$. In the same way, critical values corresponding to critical points in $C_1$ are close to $p_2$ and so on.
The fact that the critical values tend to the points \( p_0, p_1, \ldots, p_{N-1} \) does not mean that the corresponding critical values belong to the trap doors \( T_0, T_1, \ldots, T_{N-1} \), respectively. However, when the order of the poles \( d_0, d_1, \ldots, d_{N-1} \) satisfy the arithmetic condition \( \mathcal{I} \) (see definition 1.1) we will see that if \( \lambda \) is sufficiently small, all the free critical points of \( f_\lambda \) map within one of the trap doors after exactly one iterate of \( f_\lambda \).

First, observe that all free critical points belong to the basin of attraction of infinity. Let \( c_\lambda \in C_0 \) and let \( v_0 \) denote the corresponding critical value. As \( \lambda \to 0 \), \( \tilde{v}_0 \) approaches \( p_1 \) at a rate of \( \lambda^{2/(d_0+2)} \). Hence, we can write \( \tilde{v}_0 = p_1 + k_0^2 \lambda^{2/(d_0+2)} \). Introducing this value in \( f_\lambda \) we can see that the image of this point is close to \( \infty \) when \( 2d_1 > d_0 + 2 \) in the following expression

\[
\frac{\lambda}{\prod_{i=0}^{N-1} (\tilde{v}_0 - p_i)^{d_i}} \to \infty \text{ as } \lambda \to 0.
\]

As \( \lambda \) tends to 0, note that if \( f_\lambda(\tilde{v}_0) \) is close to \( \infty \), then \( \tilde{v}_0 \) is inside of the corresponding trap door \( T_1 \). In the same way, for sufficiently small values of \( \lambda \), if \( d_{i+1} > d_i + 1 \) then the image of the critical value corresponding to a critical point in \( C_i \) is close to \( \infty \). Hence the critical value, corresponding to a critical point in \( C_i \), belongs to \( T_{i+1} \). \( \square \)

To establish the topological characteristics of the Julia and Fatou sets of \( f_\lambda \) we use the Riemann-Hurwitz formula (see, for example,[11]).

**Theorem 4.2.** (Riemann-Hurwitz formula) Let \( U \) and \( V \) be connected regions in the complex plane such that the connectivity (number of boundary components) of \( U \) is \( u \) and the connectivity of \( V \) is \( v \) and such that a map \( g : U \to V \) is proper of degree \( k \) and contains \( n \) critical points in \( U \). Then,

\[
u - 2 = k(v - 2) + n.
\]

Since all the critical points of \( f_\lambda \) are attracted to infinity, the Fatou set is the basin of attraction of infinity. Thus we can study the Fatou set by considering the connectivity of the connected components in the Fatou set. To do so, first we study the preimages of \( B_\lambda \), second the preimages of the trap doors \( T_i \) and finally the rest of the components of the Fatou set.

In our case, \( B_\lambda \) is a simply connected domain and there are \( N \) trap doors, that is \( N \) disjoint preimages of \( B_\lambda \) that are also simply connected. Each trap door \( T_i \) surrounds the pole at \( p_i \), for every \( 0 \leq i \leq N - 1 \). The pole \( p_i \) is a critical point of order \( d_i - 1 \) and infinity is a critical point of order 1. Then all the preimages of points in \( B_\lambda \) lie in \( B_\lambda \cup T_0 \cup T_1 \cup \ldots \cup T_{N-1} \). The set \( B_\lambda \) is mapped 2-to-1 onto itself and the sets \( T_i \) are mapped at least \( d_i \)-to-1 onto \( B_\lambda \) because \( p_i \in T_i \), for every \( 0 \leq i \leq N - 1 \). Since their boundaries are mapped to \( \partial B_\lambda \) we have that the trap doors are bounded by inverted copies of the boundary of \( B_0 \) and not by
quasicircles (see Figure 5). Since the degree of the map $f_\lambda$ is $2 + d_0 + d_1 + \ldots + d_{N-1}$ we have that each trap door $T_i$ is mapped onto $B_\lambda$ with exactly degree $d_i$ under $f_\lambda$.

It is easy to see that $B_\lambda$ is disjoint from $T_i$ and $T_i \cap T_j = \emptyset$ for $i \neq j$ because they are in different components of the homeomorphic copy of the filled Julia set of $f_0$. Since the boundaries of the $T_i$ are in $J(f_\lambda)$ we have that the Julia set is disconnected and then, by a classical result from complex dynamics (see, for example, [11]), it must consist of uncountably many distinct connected components.

Figure 5: Dynamical plane for $f_\lambda(z) = z^2 - 1 + 10^{-22}/(z^7(z + 1)^5)$ near the two trap doors.

Fix $d_0, d_1, \ldots, d_{N-1}$ which satisfy arithmetic condition $I$ (see definition 1.1) and let $\lambda$ be chosen sufficiently small. Now we can study the preimages of the trap doors $T_i$ for every $0 \leq i \leq N - 1$. There are two different cases: the preimage of $T_1$ and the preimages of the rest of the trap doors. We consider each case separately.

Let $i \neq 1$ and consider the trap door $T_i$. From Theorem A, we know that $\partial B_\lambda$ is homeomorphic to $J(f_0)$ and that the dynamics of $f_\lambda$ are conjugate to the dynamics of $f_0$ restricted to the respective sets. Consider the components of the filled unperturbed Julia set that do not contain a point of in the superattracting cycle. There is no change to the dynamics of these components because $\lambda$ is small enough so that the singular perturbation occurs outside of those components. Thus, for $|\lambda|$ small enough, there is a preimage of $T_i$ that is simply connected and contains the preimage of $p_{i-1}$ that is located inside a bulb that corresponds to a bulb outside of the superattracting $N$-cycle in the unperturbed map. We also have $d_k$ preimages of $T_i$ that are simply connected and are symmetrically distributed around each pole $p_k$ where $k \neq i - 1$. Hence we have $1 + d_0 + \ldots + d_{i-1} + d_{i+1} + \ldots d_{N-1}$
preimages of $T_i$. The degree of $f_\lambda$ is $2 + d_0 + \ldots + d_{N-1}$ and it follows that the other $d_i + 1$ preimages of $T_i$ are in an annulus that surrounds $p_{i-1}$ and contains the $d_i + 1$ critical points in $C_{i-1}$.

To show that these preimages of $T_i$ are in an annulus we apply the Riemann-Hurwitz formula. If we assume that the preimages are not connected we get a contradiction on the number of preimages of points of the trap doors. Suppose that the $d_i + 1$ critical points that surround $p_{i-1}$ (the critical points in $C_{i-1}$) and are mapped inside $T_i$ are not in one connected component. Suppose that there are two groups of critical points in different simply connected components of $f^{-1}_\lambda(T_i)$, one with $u$ critical points and one with $v$ critical points such that $u + v = d_i + 1$. Notice that there must be $d_i + 1$ preimages of points in $T_i$ in these components (since one preimage of $T_i$ is at $-p_{i-1}$ and the other preimages are around the poles). Then the component that contains $u$ critical points contains at least $u + 1$ preimages of points in $T_i$ and the other component contains at least $v + 1$ preimages of points in $T_i$. This gives a contradiction.

We now consider the preimages of $T_1$. In this case we have $d_k$ preimages of $T_1$ that are simply connected and are symmetrically distributed around each pole $p_k$ where $k \neq 0$. Thus, there are $d_1 + \ldots + d_{N-1}$ preimages of $T_1$. Using the same argument as before, the other preimage of $T_1$ is now an annulus. In this case the annulus contains $d_0 + 2$ critical points (the critical points in $S_0$), and using the Riemann-Hurwitz formula, the map $f_\lambda$ maps this annulus onto the trap door $T_1$ with degree $d_0 + 2$.

Finally, a simple argument describes the connectivity of all further preimages. Since all the critical points are either already accounted for or are contained in one of $B_\lambda$ (the points of infinity), $T_i$ (the poles), or in the annuli around $p_i$ (the critical points in $C_{i-1}$) the Riemann-Hurwitz formula indicates that the preimage of each annulus is another annulus and the preimages of $B_\lambda$ are simply connected domains.

5 The Julia set

In this section, we use the previous propositions to construct countably many Cantor sets of simple closed curves. We show that there are $N$ such sets inside of the components which correspond to the connected components of the unperturbed Julia set which contain the superattracting cycle and infinitely many other such sets in the preimages of those sets. However, this is an incomplete description since it is known that repelling periodic points are dense in the Julia set. The boundary of $B_\lambda$ contains repelling periodic points exactly as the basilica. We show that the remainder of the Julia set consists of Cantor sets of point components which contain the other repelling periodic points.

5.1 Cantor sets of simple closed curves

Recall that when $\lambda = 0$, $f_\lambda$ has a superattracting cycle of period $N$ given by $p_0, p_1, \ldots, p_{N-1}$. Denote the immediate basin of attraction of $p_i$ under the appropriate iterate of $f_\lambda$ when
\[ \lambda = 0 \text{ by } U_i \text{ and the boundary of each } U_i \text{ by } \gamma_i. \] The set \( U_0 \) maps 2-to-1 over the set \( U_1 \) and \( U_j \) maps 1-to-1 over \( U_{j+1} \). The boundary curves \( \gamma_i \) map over each other in an analogous way.

When \( \lambda \neq 0 \), the sets \( U_i \) and their boundaries persist due to the holomorphic motion argument presented earlier (see §3). So, for \( f_\lambda \) there are analogous regions \( U_0(\lambda), \ldots, U_{N-1}(\lambda) \) and boundary curves \( \gamma_i(\lambda) \) for \( i = 0, \ldots, N - 1 \). The dynamics on the boundary curves is the same as the unperturbed case, however the dynamics within the \( U_i(\lambda) \) regions is very different due to the presence of the poles located at each point of the superattracting cycle of \( f_0 \). The boundary of the trap door at \( p_i \) maps as a \( d_i \)-to-1 covering of the boundary of \( B_\lambda \). Therefore, we call the boundary of the trap door within the set \( U_i \) a \( d_i \)-fold inverted copy of the Julia set of \( f_0 \).

Inside \( U_{i+1}(\lambda) \) there is a preimage of the complement of \( U_i(\lambda) \). We denote this set \( S_{i+1}(\lambda) \). Denote the boundary of \( S_{i+1}(\lambda) \) by \( \xi_{i+1}(\lambda) \). Note that the set \( S_{i+1}(\lambda) \) contains the trap door in \( U_{i+1}(\lambda) \) and also much more. In particular, it contains all of the “decorations” that point toward the pole at \( p_{i+1} \). However, by the previous section, \( S_{i+1}(\lambda) \) cannot contain any critical points except the pole \( p_{i+1} \). Indeed, by the Riemann-Hurwitz formula, the preimage of the set \( S_{i+1}(\lambda) \) is an annulus denoted by \( A_i \) in the set \( U_i(\lambda) \) which surrounds the set \( S_i(\lambda) \). This annulus contains the free critical points that surround the pole \( p_i \).

\[ \begin{align*}
\gamma_1(\lambda) & \quad \xi_1(\lambda) & \quad S_1(\lambda) & \quad B_1^1 \\
\xi_0(\lambda) & \quad \xi_0(\lambda) & \quad S_0(\lambda) & \quad B_1^1 \\
U_1(\lambda) & \quad A_1 & \quad A_0 & \quad B_0^0
\end{align*} \]

Figure 6: The regions \( U_0(\lambda) \) and \( U_1(\lambda) \) in the case where the unperturbed Julia set is the basilica.

Now, consider the case where the unperturbed map is the basilica, i.e., \( f_\lambda(z) = z^2 - 1 + \lambda/(z^d_0(z + 1)^{d_1}) \) where \( d_0 \) and \( d_1 \) satisfy the arithmetic condition \( \mathcal{L} \). (The cases for all other cycle lengths can be proven in the same way as the following case. We restrict to this case so that the notation is more manageable). The sets and boundary curves described
above are displayed in Figure 6. By the approximations presented earlier, we know that all of the free critical points map inside of the trap doors (see section § 4). Using the argument involving the Riemann-Hurwitz formula, the preimage of set \( S_0(\lambda) \) is the annulus \( \mathcal{A}_1 \) and the preimage of the set \( \mathcal{S}_1(\lambda) \) is the annulus \( \mathcal{A}_0 \). Consider the annulus bounded by the curves \( \gamma_0(\lambda) \) and \( \xi_0(\lambda) \). Call this annulus \( \mathcal{Q}_0 \). Similarly, the annulus bounded by \( \gamma_1(\lambda) \) and \( \xi_1(\lambda) \) is denoted \( \mathcal{Q}_1 \). Both boundary curves of \( \mathcal{Q}_0 \) map over the curve \( \gamma_1(\lambda) \): the curve \( \gamma_0(\lambda) \) maps over it twice and \( f_\lambda \) maps \( \xi_0(\lambda) \) \( d_0 \)-to-1 over \( \gamma_1(\lambda) \). Thus, \( \mathcal{Q}_0 \) is mapped \( d_0 + 2 \) times over \( \mathcal{Q}_1 \). Similarly, \( \mathcal{Q}_1 \) is mapped \( d_1 + 1 \) times over \( \mathcal{Q}_0 \).

Each \( \mathcal{Q}_i \) can be divided into three subannuli: \( B_i^0, B_i^1, \) and \( A_i \). Consider the two annuli \( B_0^0 \) and \( B_0^1 \) inside of \( \mathcal{Q}_0 \). Since the boundary curves \( \gamma_0(\lambda) \) and \( \xi_0(\lambda) \) are both mapped by \( f_\lambda \) over \( \gamma_1(\lambda) \) it follows that both \( B_0^0 \) and \( B_0^1 \) map over the annulus \( \mathcal{Q}_1 \): \( B_0^0 \) with degree 2 and \( B_0^1 \) with degree \( d_0 \). Thus, there is a preimage of the annulus \( \mathcal{A}_1 \) inside of both \( B_0^0 \) and \( B_0^1 \). Similarly, there will be a preimage of the annulus \( \mathcal{A}_0 \) in both the annuli \( B_1^0 \) and \( B_1^1 \). We continue this process inductively infinitely many times. This construction yields a pair of Cantor sets of simple closed curves in \( U_0(\lambda) \) and \( U_1(\lambda) \) as in [12]. We call these Cantor sets of simple closed curves \( \Lambda_0(\lambda) \) and \( \Lambda_1(\lambda) \). In each \( \Lambda_i(\lambda) \), there are countably many “boundary” curves which eventually map to \( \gamma_i \) and also an uncountable collection of buried curves that map to other buried curves in \( \Lambda_0(\lambda) \cup \Lambda_1(\lambda) \) but never to either \( \gamma_i \) curve.

For each component corresponding to a connected component of the unperturbed Julia set, there will be a preimage of either \( \Lambda_0(\lambda) \) or \( \Lambda_1(\lambda) \). Note that any point in this portion of the Julia set will eventually map to either \( \Lambda_0(\lambda) \) or \( \Lambda_1(\lambda) \) and then remain in the union of \( U_0(\lambda) \) and \( U_1(\lambda) \) for all further iterates. This series of preimages produces countably many Cantor sets of simple closed curves in the Julia set of \( f_\lambda \). We have shown:

**Proposition 5.1.** Let \( \lambda \) be sufficiently small, \( c \neq 0 \) be chosen to be the center of a hyperbolic component of the Mandelbrot set, and suppose \( d_0, d_1, \ldots, d_{N-1} \) satisfy the arithmetic condition \( \mathcal{I} \). Then the Julia set of \( f_\lambda \) contains countably many Cantor sets of simple closed curves.

There is actually much more structure in the Julia set of the family \( f_\lambda \). In the above argument, the sets \( \Lambda_i \) were generated using preimages of the curves \( \gamma_i \) which is only a small part of the boundary of \( B_\lambda \). If we take preimages of the full boundary of \( B_\lambda \), we can see that the curves \( \xi_i \) are actually \( d_i \)-fold inverted copies of \( J(f_0) \) rather than simple closed curves. We consider the preimages of the other components to be “decorations” on the boundary curves of \( \Lambda_i \). The \( d_i \) decorations attached to the \( \xi_i \) all point toward the associated pole at \( p_i \).

We continue with the example of the perturbed basilica. In \( S_0(\lambda) \) we can observe \( d_0 \) large decorations that correspond to preimages of \( U_0 \). The preimage of \( S_0(\lambda) \) in \( U_0 \) is the annulus \( \mathcal{A}_1 \). The inner boundary of \( \mathcal{A}_1 \) maps onto \( \xi_0 \) with degree \( d_1 \). Thus there are \( d_0d_1 \) large decorations that point inside of the annulus \( \mathcal{A}_1 \). The outer boundary of \( \mathcal{A}_1 \) has degree 1 so it maps once over \( \xi_0 \). It has \( d_0 \) large decorations that point toward the interior of the annulus \( \mathcal{A}_1 \). On the left-hand side of Figure 5, we can see 7 large decorations on the outer boundary of \( \mathcal{A}_1 \). There is a slight complication in the number of large decorations inside the
annulus $A_0$. The outer boundary maps to $\xi_1$ with degree 2 while the inner boundary maps to $\xi_1$ with degree $d_0$. Thus there are 10 preimages of $U_1(\lambda)$ pointing toward the interior of the annulus. On the right-hand side of Figure 5, there are actually 20 “large decorations.” The additional 10 decorations correspond to preimages of the component containing the point $z = 1$. Notice in the unperturbed basilica that $f_0(-z) = f_0(z)$. Thus, the component containing the point $z = 1$ and the component containing the point $z = -1$ are the same size.

There are decorations on all curves which eventually map to the boundary of $B_\lambda$. All of the buried curves in $\Lambda_i$ and their preimages never map to the boundary of $B_\lambda$. Therefore, these are simple closed curves, i.e., curves without decorations. This can be proven by performing quasiconformal surgery on the component of the unperturbed filled Julia set containing 0, just as in [1]. What remains is conjugate to a map of the form, $z^3 + C/z^3$ and is a Cantor set of quasicircles since the critical values lie within the trap door. Adding back the decorations will result in attachments on only those curves which eventually map to the boundary of the immediate basin of attraction of infinity. Therefore buried curves must be quasicircles. We have just shown:

**Proposition 5.2.** In any preimage of a Cantor set of simple closed curves, $\Lambda_i(\lambda)$

1. Each unburied curve comes with attachments which are preimages of $\partial B_\lambda$.
2. Each buried curve is a simple closed curve without decorations.

### 5.2 Cantor sets of point components

In the previous sections, the only portions of the Julia set that could contain periodic points were located in $\partial B_\lambda$ or in one of the Cantor sets of closed curves, $\Lambda_0(\lambda), \Lambda_1(\lambda), \ldots, \Lambda_{N-1}(\lambda)$. The countable many preimages of $\partial B_\lambda$ and the preimages of the $\Lambda_i(\lambda)$ cannot contain periodic points since points within these sets eventually map to $\partial B_\lambda$ or to the union of the $\Lambda_i(\lambda)$ and then remain there for all subsequent iterates. Thus, our description of the Julia set is incomplete because it is known that repelling periodic points are dense in the Julia set. In this section, we prove that the remainder of the Julia set consists of an uncountable collection of point components.

Recall that the point $p_i$ of the superattracting cycle is contained in the component of $K(f_0)$ denoted $U_i$ and that these sets persist (but not the super-attracting cycle) when $\lambda \neq 0$ due to the holomorphic motions argument (see § 3). The filled Julia set of $f_0$ consists of infinitely many other such open disks. For $j > N - 1$, let $U_j$ denote a unique open disk. The way that the $U_j$ are indexed is not important to the argument that follows. Let $U_j(\lambda)$ denote the corresponding open disk for $f_\lambda$. We shall consider just those points of the Julia set that are not in $\partial B_\lambda$ or any of its preimages. We assign an itinerary to each point in this set.

We assign an itinerary to each point $z$ in the usual way, i.e., $S(z) = (s_0s_1\ldots)$ where $s_j = \ell$ if and only if $f_\lambda^j(z) \in U_\ell(\lambda)$. Since, by assumption, the orbit of $z$ never lands on $\partial B_\lambda$ there is no ambiguity in this definition.
Let $G_\lambda$ be the set of points in the Julia set of $f_\lambda$ that do not lie either in $\partial B_\lambda$ or in any of its preimages or in one of the Cantor sets $\Lambda_i(\lambda)$ or any of its preimages. We say that the itinerary $s = (s_0s_1\ldots)$ is allowable if it corresponds to a point $z \in G_\lambda$. Which sequences are allowable clearly depends on the choice of how the components of $K(f_0)$ are indexed.

Suppose $s = (s_0s_1\ldots)$ is an allowable itinerary. Suppose some entry of the sequence, $s_j$, is an element $D_i$ of the set $D = \{0, 1, \ldots, (N - 1)\}$. Then either $s_{j+1}$ is $D_{i+1}$ or it is not. If it is not, then we call $s_j$ a departure index, because this entry is where the itinerary departs from the itinerary of any 2-block in the superattracting $N-$cycle of $f_0$, i.e., any 2-block in the itinerary $01\ldots(N-1)$. Note that since we are working modulo $N$, if the itinerary is following the itinerary of the unperturbed map, the entry we would expect to follow the entry $(N-1)$ is 0. Furthermore, suppose the entry $s_j$ is any entry which is not an element of $D$. The orbit of such a point would follow the dynamics of the unperturbed map until an entry in its itinerary is from the set $D$. This is due to the fact that the poles are located along the original superattracting cycle. The behavior far from the poles is not altered by the perturbation. Once the itinerary of this orbit contains an element from the set $D$, it could either follow the cycle for any finite number of entries or could immediately depart from the cycle. For this reason, there will be infinitely many entries in an allowable itinerary from the set $D$ and, by the same logic, infinitely many of these entries must be departure indices since an itinerary for a point from the set $G_\lambda$ cannot eventually end in the repeating sequence $01\ldots(N-1)$.

**Proposition 5.3.** Suppose $s = (s_0s_1\ldots)$ is an allowable itinerary that does not end in the repeating sequence $012\ldots(N-1)$. Then the set of points with itinerary $s$ is a Cantor set in $J(f_\lambda)$. Moreover, every point in this Cantor set is a point component of $J(f_\lambda)$.

Before the proof of this statement, we will give two examples. As before, we use the example of the perturbed basilica. In both of these examples $D = \{0, 1\}$. In other words, an itinerary has the ability to depart from the itinerary of the superattracting cycle whenever the corresponding orbit enters the component containing either $z = 0$ or $z = -1$.

**Example 1: The set with itinerary $(02)$.**

Consider the set of points in the Julia set with itinerary $(02)$. In this example, every entry that is a 0 is a departure index since 0 should be followed by a 1 if it is following the superattracting 2-cycle in the unperturbed basilica. Every entry that is a 2 is not a departure index. This set is allowable because the set $U_0$ maps over all of $\hat{C}$ and the set $U_2$ maps in a 1-to-1 fashion over $U_0$. First consider the set with partial itinerary 02, which we will denote $W_{02}$. Since $\xi_0$ maps $d_0$-to-1 over $\gamma_1$, there are $d_0$ small copies of $U_0$ in the interior of the set $S_0$. Attached to each one of those copies of $U_0$ is one copy of the set $U_2$. Thus, the set with partial itinerary 02 consists of $d_0$ small subdisks in the set $U_0$. The set with partial itinerary 202 consists of $d_0$ subdisks inside of $U_2$ since $U_2$ maps in a 1-to-1 fashion over $U_0$. Next we turn to the set with partial itinerary 0202, i.e., the set in $U_0$ that maps over the $d_0$ subdisks in $U_2$ with partial itinerary 202. Note that each of the subdisks in $W_{02}$ maps over $U_2$. Thus, there are $d_0$ subdisks nested within each of the subdisks in $W_{02}$ that
map to $W_{202}$. It follows that $W_{0202}$ consists of $(d_0)^2$ subdisks. Continuing in this fashion, every other iterate will yield a multiple of $d_0$ smaller, nested subdisks. By standard results in complex dynamics, the intersection of all of these sets yields a Cantor set of points with itinerary $\langle 012 \rangle$. Any point in the collection is surrounded by arbitrarily small annuli that lie in the Fatou set (preimages of the annulus $\mathcal{A}_0$) thus each point in this Cantor set is actually a point component of the Julia set. See Figure 5.2 for a sketch of the first few nested disks.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{nested_disks.png}
\caption{Sketch of some of the nested disks which generate a Cantor set of point components in Example 1.}
\end{figure}

**Example 2: The set with itinerary $\langle 012 \rangle$.**

Next, we consider the set of points whose itinerary is $\langle 012 \rangle$. In this example, every entry that is a 1 is a departure index since 1 should be followed by a 0 (rather than a 2) if it is following the superattracting 2-cycle in the unperturbed basilica. The remaining 0 and 2 entries are not departure indices. This allowable sequence is different from the first example because the partial itinerary 01 follows the attracting cycle before the sequence departs from the cycle. Allowable itineraries may follow the cycle for any finite number of iterates provided there is a departure index afterwards. This makes the construction slightly more complex.

First consider the set $W_{12}$, i.e., the set with partial itinerary 12. Since the curve $\xi_1$ in $U_1$ maps to $\gamma_0$ and the set $U_2$ is attached to $\gamma_0$, there will be $d_1$ disks in the interior of $S_1$ that map to $U_2$. Next, we consider the set $W_{012}$. Since the annulus $\mathcal{A}_0$ maps in a $(2 + d_0)$-to-1 fashion over the set $S_1$, the set $W_{012}$ consists of $2d_1 + d_0d_1$ disks which are some of the decorations that are in the interior of the annulus $\mathcal{A}_0$: $2d_1$ on the outer boundary of the annulus and $d_0d_1$ on the inner boundary of the annulus. Since $U_2$ maps 1-to-1 over $U_0$, $W_{2012}$
consists of the same number of disks within the set $U_2$. Continuing in this fashion, we find another Cantor set of points with this itinerary since all of the disks are nested within each other. Just as in the first example, these are point components of the Julia set since each point is surrounded by arbitrarily small annuli in the Fatou set. See Figure 5.2 for a sketch of the first few nested disks.

Figure 8: Sketch of some of the nested disks which generate a Cantor set of point components in Example 2.

Now we turn to the proof of the proposition which follows in the same way as the above examples.

Proof. Suppose that $s = (s_0 s_1 s_2 \ldots)$ is an allowable itinerary. Since $s \in \mathcal{G}$, $s$ must contain infinitely many entries $D_i$ from the set $\mathcal{D}$. Since $\mathcal{D}$ is a set with finitely many members, at least one of the $D_i$ occurs infinitely often in the sequence $s$. Without loss of generality, assume that the entry 0 occurs infinitely many times in $s$ and also that the first entry of $s$ is 0, i.e., $s = (0 s_1 s_2 \ldots)$. We can rewrite the sequence $s$ as $(0 \tau_1 0 \tau_2 0 \ldots)$ where $\tau_i$ denotes all of the nonzero entries between consecutive 0’s.

There are only four distinct types of 2-blocks of consecutive entries that can occur in the sequence $s$ and, more generally, in any allowable itinerary. The first is a block of the form 01. When this 2-block occurs, there are $d_0 + 2$ disks within $U_0$ that map to $U_1$. When the 2-block $D_i D_{i+1}$ occurs, there are $d_i + 1$ disks within $U_{D_i}$ that map to $U_{D_{i+1}}$. In this case when $D_i = N-1$ then $D_{i+1} = 0$. Next, when the 2-block takes the form $D_i s_i$, where $s_i \neq D_{i+1}$, there are $d_i$ disks within $U_{D_i}$ that map within $U_{s_i}$. Finally, when the 2-block is of the form $s_i s_{i+1}$, where $s_i \notin \mathcal{D}$, there is only 1 disk in $U_{s_i}$ that maps to $U_{s_{i+1}}$. 

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As before, we can consider those points with partial itinerary 0 $\tau_1 0$. We claim that the set of points in $U_0$ following this partial itinerary corresponds to disks nested within each other. In order to compute the number of such disks it is enough to consider the product of the number of disks resulting from each 2-block in the partial itinerary. In the next step, we consider the points with partial itinerary 0 $\tau_1 0 \tau_2 0$. We can determine the number of disks with this partial itinerary by creating a product similar to the one in the first step. These disks are nested within those of partial itinerary 0 $\tau_1 0$. Continuing in this fashion, standard arguments from complex dynamics yield a Cantor set of points with the itinerary $s$. If the itinerary $s$ begins with an entry different from zero, all we need do is pull the Cantor set of points back into the corresponding $U_i$. Like in both examples presented earlier, there are arbitrarily small Fatou components surrounding each of these points, preimages of the annuli $A_i$, hence they are point components of the Julia set.

6 The perturbed basilica

In the final section, we turn to the example of the perturbed basilica once more to explore some of the details regarding the arithmetic condition $I$. We consider the function

$$f_\lambda(z) = z^2 - 1 + \frac{\lambda}{z^{d_0}(z+1)^{d_1}}.$$ 

All of the theorems of this paper can be proven when the arithmetic condition $I$ is satisfied and for sufficiently small values of $|\lambda|$. In this case, the arithmetic condition is

$$2d_1 > d_0 + 2 \quad \text{and} \quad d_0 > d_1 + 1.$$ 

Figure 9 shows a graphical representation of the values of $d_0$ and $d_1$ that satisfy $I$. In the figure, it is clear that the smallest values that satisfy $I$ are $d_0 = 7, d_1 = 5$. Notice that since the region is unbounded, there is an infinite collection of pairs of numbers that will also satisfy $I$. Hereafter, we restrict to the specific case where $d_0 = 7, d_1 = 5$.

Notice that the degree $f_\lambda$ is 14 and so there are 26 critical points counted with multiplicity. Infinity is a critical point of order 1, 0 is a critical point of order 6 and -1 of order 4. The other critical points of $f_\lambda$ that satisfy the equation

$$2c^5(c + 1)^6 = \lambda(7(c + 1) + 5c)$$

and we see that when $\lambda \to 0$ there are 9 critical points that approach 0, and 6 critical points that approach $-1$. The critical values corresponding to these 15 “free” critical points are determined by

$$v = f_\lambda(c) = c^2 - 1 + \frac{2c^2(c + 1)}{7(c + 1) + 5c}.$$ 

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Note that if $c \to 0$ then $v \to -1$ and if $c \to -1$ then $v \to 0$.

Let $C_0$ denote the set of 9 critical points around 0 and $C_{-1}$ denote the 6 critical points around $-1$. Let $c_0$ be one of the critical points in $C_0$ and $c_{-1}$ be one of the critical points in $C_{-1}$. Then, we can write

$$c_0 \approx \left(\frac{7}{2} \lambda\right)^{1/9}, \quad c_{-1} \approx -1 + \left(\frac{5}{2} \lambda\right)^{1/6}.$$

We can find the critical values corresponding to $c_0$ and $c_{-1}$, respectively, by computing $f_\lambda(c_0)$ and $f_\lambda(c_{-1})$. We get

$$v_0 = f_\lambda(c_0) \approx -1 + \frac{9}{7} \left(\frac{7}{2} \lambda\right)^{2/9} = \tilde{v}_0$$

and

$$v_{-1} = f_\lambda(c_{-1}) \approx -\frac{12}{5} \left(\frac{5}{2} \lambda\right)^{1/6} = \tilde{v}_{-1}.$$

It is easy to check that when $\lambda \to 0$ we have $v_0 \to -1$ at a rate proportional to $\lambda^{2/9}$ and $v_{-1} \to 0$ at a rate proportional to $\lambda^{1/6}$. We can compute now the images of the critical values to see if they are close to infinity when $\lambda$ is small. If this happens then we deduce that for $\lambda$ small the critical values $v_0$ and $v_{-1}$ lie in the trap doors around $-1$ and 0, respectively.

$$\omega_0 = f_\lambda(\tilde{v}_0) = \tilde{v}_0^2 - 1 + \frac{\lambda}{\tilde{v}_0^2 \left(\frac{9}{7} \lambda^{2/9}\right)^5} \to \infty$$

Figure 9: Sketch of the region where arithmetic condition $I$ is satisfied.
\[
\omega_{-1} = f_\lambda(\tilde{v}_{-1}) = \tilde{v}_{-1}^2 - 1 + \frac{\lambda}{\left(-\frac{72}{5} \left(\frac{5}{2}\lambda\right)^{1/6}\right)^7 \tilde{v}_{-1}} \rightarrow \infty.
\]

From these two equations we see that \(\omega_0\) and \(\omega_{-1}\) tend to infinity when \(\lambda\) tends to zero so we conclude that \(v_0\) and \(v_{-1}\) lie in the trap doors as we wanted to show.

This implies that we know the fate of the orbit of each critical point of \(f_\lambda\). We have 9 critical points that surround the origin and are mapped inside \(T_1\) and 6 critical points that surround \(-1\) and are mapped inside \(T_0\) (see Figure 5). These two trap doors are disjoint preimages of the immediate basin of infinity \(B_\lambda\). Notice that \(B_\lambda\) is mapped to itself in a 2-to-1 fashion, the set \(T_0\) is mapped 7-to-1 onto \(B_\lambda\) and \(T_1\) is mapped 5-to-1 onto \(B_\lambda\).

Finally, in the special case of the basilica we can give a general idea for the size of \(|\lambda|\) required for our results to hold. To generate this estimate we need to know the approximate sizes of the immediate basin of attraction of infinity, \(B_\lambda\), and the two trap doors: \(T_0\) and \(T_1\).

First we approximate the size of \(B_\lambda\). From \(f_\lambda\) it is easy to see that if \(|\lambda| < 1/10\) then \(B_\lambda\) contains the open set \(D_\infty = \{z \in \mathbb{C}; |z| > 4\}\). Second we can find a small disk, \(D_0 = \{z \in \mathbb{C}; |z| < \delta\}\), that is completely contained in the trap door \(T_0\). This disk consists of the points that will map to \(D_\infty\) after one application of \(f_\lambda\). When \(z\) is close to 0, we have that
\[
|f_\lambda(z)| \geq \frac{|\lambda|}{|z|^7} - 1 > 4,
\]
from the above expression taking \(\delta = \left(\frac{|\lambda|}{5}\right)^{1/7}\) we see that the trap door \(T_0\) contains the open disk \(D_0 = \{z \in \mathbb{C}; |z| < \left(\frac{|\lambda|}{5}\right)^{1/7}\}\). In the same way we can find a second disk, \(D_1\) centered at \(-1\), and completely contained in the trap door \(T_1\), given by \(D_1 = \{z \in \mathbb{C}; |z+1| < \left(\frac{|\lambda|}{4}\right)^{1/5}\}\).

Now we can find the approximate size of \(\lambda\). The idea is to require that the critical values, corresponding to critical points close to zero, are mapped inside the trap door \(T_1\). The critical points close to 0 are mapped to
\[
v_0 \approx -1 + \frac{9}{7} \left(\frac{7}{2} |\lambda|\right)^{2/9}.
\]
From the above estimate of \(T_1\) requiring that \(v_0 \in D_1 \subset T_1\) we have
\[
\frac{9}{7} \left(\frac{7}{2} |\lambda|\right)^{2/9} < \left(\frac{|\lambda|}{4}\right)^{1/5}.
\]

We also require that the critical values, corresponding to critical points close to \(-1\), are mapped inside the trap door \(T_0\). The critical points close to \(-1\) are mapped to
\[
v_{-1} \approx -\frac{12}{5} \left(\frac{5}{2} |\lambda|\right)^{1/6},
\]
which
these values are in $D_0 \subset T_0$ when

$$\frac{12}{5} \left( \frac{5}{2} |\lambda| \right)^{1/6} < \left( \frac{|\lambda|}{5} \right)^{1/7}.$$ 

Thus, we can apply our results as long as $|\lambda|$ satisfies both inequalities, in this concrete case, when $|\lambda| \approx 10^{-22}$.

References


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