

# 1 Introduction

Let  $f_c(z) = z^2 + c$  be a quadratic polynomial. Its *filled Julia set* consists of points in the complex plane with bounded orbit under iteration by  $f_c$ :

$$\mathcal{K}(f_c) = \{z \in \mathbb{C} : \sup_{n \geq 0} f_c^{\circ n}(z) < \infty\}.$$

Its complement  $A_\infty(f_c) = \mathbb{C} \setminus \mathcal{K}(f_c)$  forms the *attracting basin of infinity*. The *Julia set*  $\mathcal{J}(f_c) = \partial\mathcal{K}(f_c)$  is defined as the boundary of the filled Julia set. It is well known in complex dynamics that  $\mathcal{J}(f_c), \mathcal{K}(f_c)$  are closed sets while  $A_\infty(f_c)$  is an open set. Furthermore, each of the three sets  $\mathcal{J}(f_c), \mathcal{K}(f_c)$  and  $A_\infty(f_c)$  are both forward and backward invariant under the dynamics of  $f$ .

The *Mandelbrot set*  $\mathcal{M}$  consists of parameters  $c \in \mathbb{C}$  for which  $\mathcal{J}_c$  is connected. The *main cardioid*

$$\heartsuit = \{c \in \mathbb{C} : c = \lambda/2 - \lambda^2/4, \lambda \in \mathbb{D}\}$$

is a connected component of the interior of  $\mathcal{M}$ , which consists of parameters  $c \in \mathbb{C}$  for which  $f_c$  has an attracting fixed point. When  $c \in \heartsuit$ , the Julia set  $\mathcal{J}(f_c)$  is a Jordan curve. In fact, more is true. Parameters  $c \in \heartsuit$  are *hyperbolic*. Loosely speaking, this means that  $\mathcal{J}(f_c)$  satisfies the principle of the conformal elevator: up to bounded distortion, a small piece of  $\mathcal{J}(f_c)$  looks like a large piece  $\mathcal{J}(f_c)$ . Using the principle of the conformal elevator, it can be show that is  $\mathcal{J}(f_c)$  a quasicircle: a condition which roughly means that  $\mathcal{J}(f_c)$  has no “cusps”.

In this work, we study the *Cauliflower*, which is the filled Julia set of  $f_{1/4}(z) = z^2 + \frac{1}{4}$ . In this case the Julia set  $\mathcal{J}(f_{1/4})$  is no longer a quasicircle, as it has an inward-pointing cusp at the point  $p = 1/2$ . However, according to a theorem of Carleson, Jones and Yoccoz [1, Theorem 6.1], the Cauliflower is a so-called John domain, which roughly says that it has no outward-pointing cusps.

A domain  $\Omega \subseteq \mathbb{C}$  is called **quasiconvex** if its intrinsic metric is comparable to the ambient Euclidean metric. Explicitly, this means that there exists a constant  $A \geq 1$  such that every two points  $z_1, z_2 \in \Omega$  are connected by a rectifiable path  $\gamma : [0, 1] \rightarrow \Omega$  which satisfies

$$\text{Length}(\gamma) \leq A \cdot |z_1 - z_2|.$$

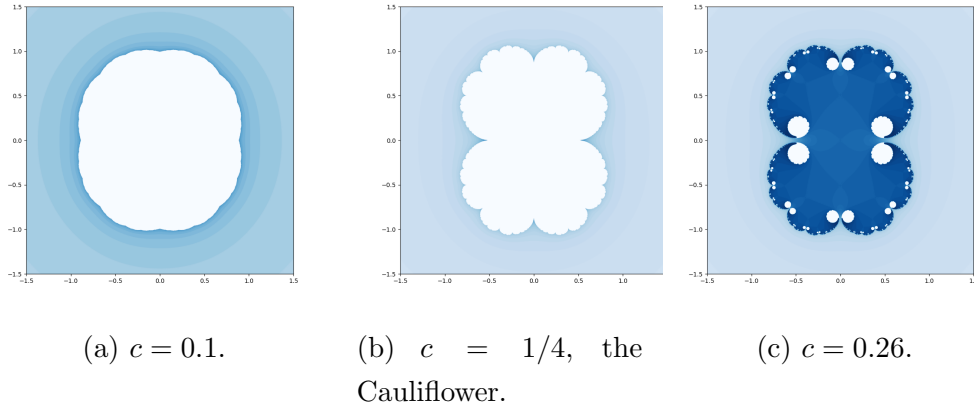


Figure 1: The Julia set  $\mathcal{J}_c$  of  $f_c$  for different values of  $c$ . When  $c > 1/4$ , the Julia set is no longer connected.

We call such a path  $\gamma$  a *quasiconvexity certificate* for  $z_1$  and  $z_2$ .

If  $\Omega$  is the interior of a Jordan curve, then by [3, Corollary F], it is enough to find certificates for points  $z_1, z_2$  that lie on the boundary curve  $\partial\Omega$ .

If  $\Omega$  is a quasiconvex Jordan domain, then its complement has a John interior; see [3, Corollary 3.4] for a proof. In this work, we strengthen the result of [1, Theorem 6.1] by showing:

**Theorem 1.1.** *The exterior of the Cauliflower,  $A_\infty(f_{1/4})$ , is quasiconvex.*

Our result also has a function-theoretic interpretation. A domain  $\Omega$  is called a  $W^{1,1}$ -extension domain if every  $u \in W^{1,1}(\Omega)$  extends to a function in  $W^{1,1}(\mathbb{C})$ .

In [2, Equation (1.1) and Theorem 1.4], it is shown that a bounded, simply connected domain is a  $W^{1,1}$  extension domain if and only if its complement is quasiconvex. Thus our result can be rephrased as follows:

**Theorem 1.2.** *The Cauliflower is a  $W^{1,1}$  extension domain.*

## 1.1 Sketch of the argument

We show quasiconvexity by an explicit construction of certificates connecting any given pair of points on the Julia set. We first build the certificates in the exterior unit

disk  $\mathbb{D}^*$ , then we transport them to the exterior of the Cauliflower by the Böttcher coordinate  $\psi : \mathbb{D}^* \rightarrow A_\infty(f_{1/4})$ , which is a conjugacy between the map  $f_0$  and  $f_{1/4}$ .

To retain control of the certificates after applying  $\psi$ , we build the certificates on  $\mathbb{D}^*$  in a manner invariant under the map  $f_0 : z \mapsto z^2$ . This makes the image of a certificate  $\eta$  in  $\mathbb{D}^*$  under the conjugacy  $\psi$  invariant under  $f_{1/4}$ . We use this invariance to show that  $\psi(\eta)$  is indeed a certificate, by employing a parabolic variant of the principle of the conformal elevator.

To facilitate the reading, we first demonstrate the proof in the hyperbolic case of maps  $f_c(z) = z^2 + c$  where  $c \in (-\frac{3}{4}, \frac{1}{4})$ . In this case, the usual conformal elevator applies. We subsequently treat the parabolic case of  $c = \frac{1}{4}$ .

## 2 The exterior disk

We connect any two boundary points  $\zeta_1, \zeta_2 \in \partial\mathbb{D}^*$  by a path in  $\mathbb{D}^*$  in a manner that respects the map  $f_0 : \zeta \mapsto \zeta^2$ . We describe these paths using the metaphor of a passenger who travels by train:

**Definition 2.1.** *Stations* are the points in  $\mathbb{D}^*$  of the form

$$s_{n,k} = 2^{1/2^n} \exp\left(\frac{k}{2^n} 2\pi i\right), \quad n \in \mathbb{N}_0, \quad k \in \{0, \dots, 2^n - 1\}.$$

These are exactly the iterated preimages of the *central station*  $s_{0,0} = 2$  under the map  $f_0$ . We refer to  $n$  as the *generation* of the station  $s_{n,k}$ . The  $2^n$  stations of generation  $n$  are equally spaced on the circle  $C_n = \{|\zeta| = 2^{1/2^n}\}$ .

We next lay two types of “rail tracks”, which we use to travel between stations.

**Definition 2.2.** Let  $s = s_{n,k}$  be a station.

1. The *peripheral neighbors* of  $s$  are the two stations  $s_{n,(k\pm 1) \pmod{2^n}}$  adjacent to  $s_{n,k}$  on  $C_n$ .
2. The *peripheral track*  $\gamma_{s,s'}$  from  $s$  to a peripheral neighbor  $s'$  is the shorter arc of the circle  $C_n$  connecting  $s$  to  $s'$ .
3. The *radial successor* of  $s$  is  $\text{RadialSuccessor}(s) = s_{n+1,2k}$ , the unique station of generation  $n+1$  on the radial segment  $[0, s]$ .

4. The *express track*  $\gamma_{s,s'}$  from  $s$  to its radial successor  $s'$  is the radial segment  $[s, s']$ .

Notice that the tracks respect the dynamics: applying  $f_0$  to a track gives a track of the previous generation.

When a passenger travels between two stations  $s_1$  and  $s_2$ , they must follow a particular itinerary from  $s_1$  to  $s_2$ . If  $s_1$  is the central station, then this itinerary is determined by the rule that the passenger stays as close as possible to its destination  $s_2$  in the angular distance. This also determines how to travel from the central station to a boundary point  $\zeta \in \partial\mathbb{D}^*$ , by continuity. See Figure 2 and the next definition.

**Definition 2.3.** Let  $\zeta = \exp(2\pi i\theta) \in \partial\mathbb{D}$ . The *central itinerary* of  $\zeta$  is a path  $\eta_\zeta = \gamma_{\sigma_0, \sigma_1} + \gamma_{\sigma_1, \sigma_2} + \dots$  from the central station to  $\zeta$ , made of tracks between the stations  $\sigma_0, \sigma_1, \dots$ . It is defined inductively as follows:

Start at the central station  $\sigma_0 = s_{0,0}$ . Suppose that we already chose  $\sigma_0, \dots, \sigma_k$ . If there is a peripheral neighbor  $\sigma$  of  $\sigma_k$  that is closer peripherally to  $\zeta$ , meaning that

$$|\text{Arg}(\zeta) - \text{Arg}(\sigma)| < |\text{Arg}(\zeta) - \text{Arg}(\sigma_k)|,$$

then take  $\sigma_{k+1} = \sigma$ . Otherwise, take  $\sigma_{k+1} = \text{RadialSuccessor}(\sigma_k)$ .

We identify the central itinerary  $\eta_\zeta$  with its sequence of stations  $(\sigma_0, \dots)$ . We record two properties of central itineraries:

- There are no two consecutive peripheral tracks in  $\eta_\zeta$ , and in particular

$$\text{Generation}(\sigma_k) \geq \frac{k}{2}; \tag{2.1}$$

- Central itineraries are essentially equivariant under  $f_0$ , in the sense that

$$f_0(\eta_\zeta) = \eta_{f_0(\zeta)} \cup [s_{0,0}, f_0(s_{0,0})]$$

for every  $\zeta \in \partial\mathbb{D}^*$ .

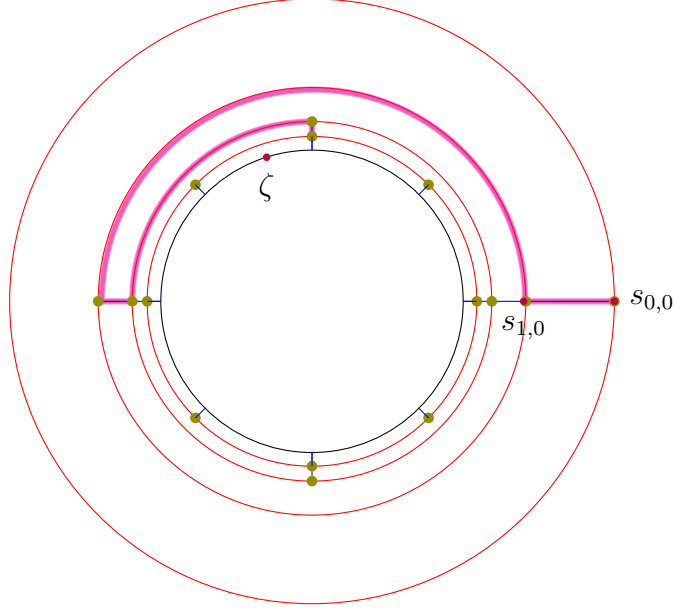


Figure 2: The central journey to a point  $\zeta$ .

**Definition 2.4.** Given two distinct boundary points  $\zeta_1, \zeta_2 \in \partial\mathbb{D}^*$ , form the central itineraries  $\eta_{\zeta_1} = (\sigma_n^1)_{n=0}^\infty$  and  $\eta_{\zeta_2} = (\sigma_n^2)_{n=0}^\infty$  and let  $\sigma = \sigma_i^1 = \sigma_j^2$  be the last station that is in both  $\eta_{\zeta_1}$  and  $\eta_{\zeta_2}$ . We define the *itinerary* between  $\zeta_1$  and  $\zeta_2$  to be the path

$$\eta_{\zeta_1, \zeta_2} = (\dots, \sigma_{i+2}^1, \sigma_{i+1}^1, \sigma, \sigma_{j+1}^2, \sigma_{j+2}^2, \dots).$$

This is a simple bi-infinite path connecting  $\zeta_1$  and  $\zeta_2$ , see Figure 3. Note that itineraries are equivariant under the dynamics: we have

$$f(\eta_{\zeta_1, \zeta_2}) = \eta_{f(\zeta_1), f(\zeta_2)} \quad (2.2)$$

for every pair of boundary points  $\zeta_1, \zeta_2 \in \partial\mathbb{D}^*$  with  $|\zeta_1 - \zeta_2| < \sqrt{2}$ .

### 3 Transporting the Rails

Let  $c \in [-\frac{3}{4}, \frac{1}{4}]$ . For these values of  $c$ , the Julia set of  $f_c : z \mapsto z^2 + c$  is a Jordan curve, and  $f_c$  has a Böttcher coordinate  $\psi$  at infinity; namely,  $\psi$  is the unique conformal

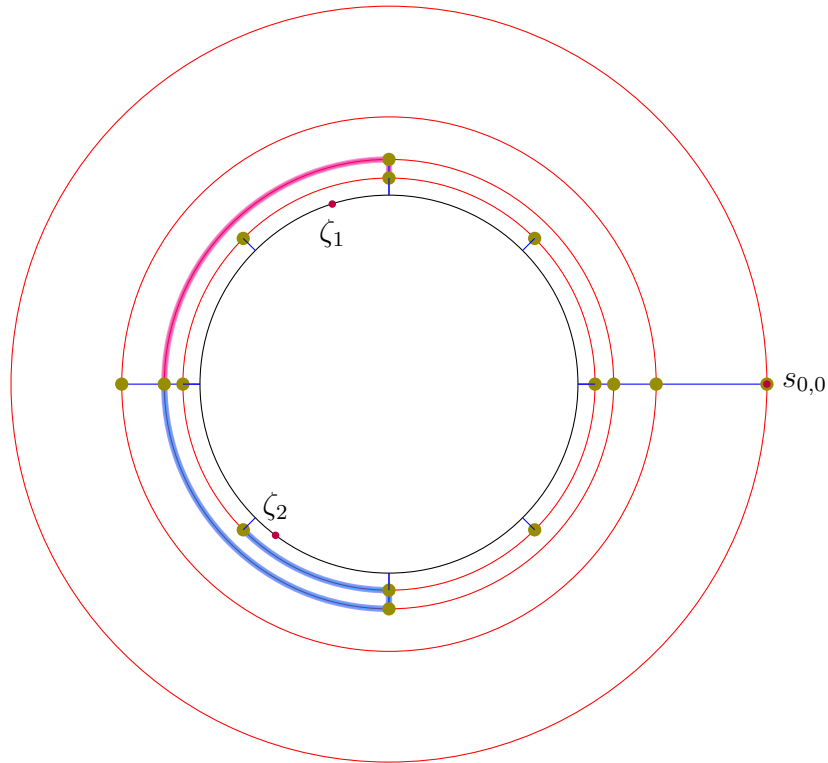


Figure 3: A quasiconvexity certificate between two points  $\zeta_1, \zeta_2$  in  $\mathbb{D}^*$ . Only the first two steps are shown.

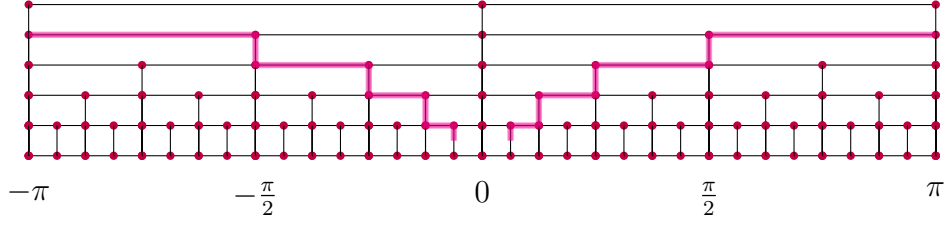


Figure 4: A convenient representation of the dyadic grid in the Böttcher coordinates. The horizontal axis is the external ray angle, and the vertical axis is the equipotential  $|\psi^{-1}(z)|$ , plotted on a log scale. The rightmost edge is glued to the leftmost edge. Stations are marked in red, and the segments connecting adjacent stations are tracks. An express track is a vertical segment, and a peripheral track is horizontal. The magenta contour bounds the region  $\mathcal{U}_{-1}$ .

map  $\mathbb{D}^* \rightarrow \text{Exterior}(\mathcal{J}_c)$  which fixes  $\infty$  and satisfies the conjugacy relation

$$f \circ \psi = \psi \circ f_0.$$

The map  $\psi$  extends to a homeomorphism between the circle  $\partial\mathbb{D}$  and  $\mathcal{J}_c$  by Carathéodory's theorem. Uniqueness is obvious from the uniqueness of the Riemann map up to rotation; see [5, Theorem 9.5] for a proof of existence, relying on the explicit construction

$$\psi(z) = \lim_{n \rightarrow \infty} (f_0)^{\circ(-n)} \circ f^{\circ n} = \lim_{n \rightarrow \infty} (f^{\circ n})^{1/2^n}.$$

We apply  $\psi$  to the rails that we constructed in  $\mathbb{D}^*$  to obtain the corresponding rails in  $\text{Exterior}(\mathcal{J}_c)$ :

**Definition 3.1.**

1. The *stations* of  $f_c$  are the points  $\psi(s_{n,k})$ .
2. The *tracks* of  $f_c$  are the curves of the form  $\psi(\gamma_{s,s'})$ , where  $\gamma_{s,s'}$  is a track. They are classified as express or peripheral according to the corresponding classification of  $\gamma_{s,s'}$ . Express tracks lie on the external rays of the filled Julia set  $\mathcal{K}_c$ , while peripheral tracks lie on the equipotentials of  $\mathcal{K}_c$ .
3. The *itinerary* between a pair of points  $(z_1, z_2)$  on  $\mathcal{J}_c$  is  $\eta_{z_1, z_2} = \psi(\eta_{\zeta_1, \zeta_2})$ , where  $\zeta_i = \psi^{-1}(z_i)$  are the corresponding points on  $\partial\mathbb{D}^*$ .

We omit  $c$  and  $\psi$  from the notation for ease of reading. It will be clear from the context whether we work in  $\mathbb{D}^*$  or in  $\text{Exterior}(\mathcal{J})$ .

Note that  $\psi((1, \infty)) \subseteq \mathbb{R}$  since  $\mathcal{J}$  is symmetric with respect to the real line, and in particular the central station  $\psi(s_{0,0})$  lies on the real axis.

## 4 Hyperbolic Maps

A quadratic map  $f_c$  is (dynamically) *hyperbolic* if its postcritical set  $\mathcal{P}$  is disjoint from its Julia set  $\mathcal{J}$ . This is equivalent to  $f$  being expanding on its Julia set:

**Theorem 4.1.** *Let  $f_c$  be a hyperbolic quadratic map, let*

$$\mathcal{P} = \overline{\{f^{\text{on}}(0) : n \geq 1\}}$$

*be the (closed) post-critical set of  $f$ , and let  $\|\cdot\|_{\text{hyp}}$  be the hyperbolic (Poincaré) metric of the domain  $\hat{\mathbb{C}} \setminus \mathcal{P}$ . Suppose  $f$  is not conjugate to  $f_0 : z \mapsto z^2$ . Then we have*

$$\|f'(z)\|_{\text{hyp}} > 1 \tag{4.1}$$

*for every  $z \in f^{-1}(\hat{\mathbb{C}} \setminus \mathcal{P})$ , and in particular for every  $z \in \mathcal{J}$ .*

For two proofs, see [5, Theorem 19.1], which also proves the converse.

**Corollary 4.2.** *Let  $f_c$  be a hyperbolic quadratic map. There exists  $\epsilon > 0$  such that every pair of points  $z, w \in \mathcal{J}$  has a forward iterate  $f^{\text{on}}$  for which*

$$|f^{\text{on}}(z) - f^{\text{on}}(w)| > \epsilon.$$

**Definition 4.3.** A point  $z \in \mathcal{J}$  is *rectifiably accessible* from  $\text{Exterior}(\mathcal{J})$  if there is a rectifiable curve  $\gamma : [0, 1) \rightarrow \text{Exterior}(\mathcal{J})$  such that  $\gamma(t) \rightarrow z$  as  $t \rightarrow 1$ .

We are now ready to show quasiconvexity in the hyperbolic case:

**Theorem 4.4.** *Let  $f : z \mapsto z^2 + c$  be a hyperbolic map.*



(i) Given  $z \in \mathcal{J}$  decompose its central itinerary into tracks,

$$\eta_z = \gamma_1 + \gamma_2 + \dots$$

We have the estimate

$$\text{Length}(\gamma_k) \lesssim \theta^k,$$

uniformly in  $z$ , for some constant  $\theta = \theta(c) < 1$ . In particular, any point on  $\mathcal{J}$  is rectifiably accessible.

(ii) The domain  $\text{Exterior}(\mathcal{J})$  is quasiconvex with the itineraries  $\eta_{z_1, z_2}$  as certificates.

*Proof.* (i) For  $c = 0$  this is a direct computation. Suppose  $c \neq 0$ , and let  $\mathcal{P}$  as before be the post-critical set of  $f$ .

Any inverse branch  $f^{-1} : \hat{\mathbb{C}} \setminus \mathcal{P} \rightarrow \hat{\mathbb{C}} \setminus \mathcal{P}$ , potentially defined only in a subdomain, is a strict hyperbolic contraction by Theorem 4.1.

Let  $B(0, R) \subset \mathbb{C}$  be a ball large enough that it contains every central itinerary. By hyperbolicity,  $\hat{\mathbb{C}} \setminus \mathcal{P}$  contains  $\overline{\text{Exterior}(\mathcal{J})}$ . Thus  $\text{Exterior}(\mathcal{J}) \cap B(0, R)$  is compactly contained in  $\hat{\mathbb{C}} \setminus \mathcal{P}$ , and there is a constant  $\theta < 1$  such that  $\|(f^{-1})'\|_{\text{hyp}} < \theta$  on  $\text{Exterior}(\mathcal{J}) \cap B(0, R)$ . Therefore,

$$\begin{aligned} \text{HypLength}(\gamma_k) &\leq \theta \cdot \text{HypLength}(f(\gamma_k)) \\ &\leq \dots \\ &\leq \theta^k \cdot \text{HypLength}(f^{\circ k}(\gamma_k)), \\ &\lesssim \theta^k, \end{aligned}$$

where the last inequality holds since  $f^{\circ k}(\gamma_k)$  lies on the real axis in case  $\gamma_k$  is an express track, or on the equipotential  $\psi(\{|z| = \sqrt{2}\})$  otherwise.

As the hyperbolic metric is equivalent to the Euclidean metric on compact subsets, we conclude that  $\text{Length}(\gamma_k) \lesssim \theta^k$  as well.

Thus any point on  $\mathcal{J}$  can be reached from the central station  $s_{0,0}$  by a curve of bounded length.

(ii) By Corollary 4.2, there exists an  $\epsilon > 0$  such that any two points are  $\epsilon$ -apart under some iterate of  $f$ . Let  $z_1, z_2 \in \mathcal{J}(f)$ . If  $|z_1 - z_2| \geq \epsilon$ , we are done since the

length of  $\eta_{z_1, z_2}$  is bounded from above uniformly by part (i). On the other hand, if  $|z_1 - z_2| < \epsilon$ , then there is an iterate  $f^{on}$  for which

$$|w_1 - w_2| := |f^{on}(z_1) - f^{on}(z_2)| \geq \epsilon \quad (4.2)$$

and we have a uniform bound on  $\frac{\text{Length}(\eta_{w_1, w_2})}{|w_1 - w_2|}$ .

Since  $f^{on}$  sends  $(z_1, z_2)$  to  $(w_1, w_2)$  and  $\eta_{z_1, z_2}$  to  $\eta_{w_1, w_2}$ , a distortion argument gives that

$$\frac{\text{Length}(\eta_{z_1, z_2})}{|z_1 - z_2|} \asymp \frac{\text{Length}(\eta_{w_1, w_2})}{|w_1 - w_2|}. \quad (4.3)$$

and we are done. Indeed, since  $z_1$  and  $z_2$  are  $\epsilon$ -close, we may find a topological ball  $B$  containing the points  $z_1, z_2$  and the itinerary  $\eta_{z_1, z_2}$  with a definite modulus inside of  $\hat{\mathbb{C}} \setminus \mathcal{P}$ , on which the map  $f^{on}$  is univalent, and apply Koebe's distortion theorem in the version of [4, Theorem 2.9] to deduce that  $\frac{|w_1 - w_2|}{|z_1 - z_2|} \asymp |(f^{on})'(x)|$  for any point  $x \in B$ , but applying  $f^{on}$  on the itinerary  $\text{Length}(\eta_{z_1, z_2})$  makes its length grow by the same factor.  $\square$

## 5 The Cauliflower

In this section,  $c = \frac{1}{4}$  and  $f = f_{1/4} : z \mapsto z^2 + \frac{1}{4}$ . Our goal is to prove the quasiconvexity of  $\text{Exterior}(\mathcal{J})$ , Theorem 5.11. This is more complicated than the hyperbolic case, because the postcritical set  $\mathcal{P}$  of  $f$  accumulates at the parabolic fixed point  $p = \frac{1}{2}$ . One no longer has a uniform bound on the distortion of inverse iterates, and we cannot immediately deduce the quasiconvexity of the itinerary  $\eta_{z_1, z_2}$  from the quasiconvexity of  $\eta_{w_1, w_2}$  using Koebe's distortion theorem. As a substitute, we present an analogue of the principle of the conformal elevator in this parabolic setting.

### 5.1 Itineraries have finite length

We first show that each itinerary  $\eta_{z_1, z_2}$  has a finite length. We will in fact show an exponential decay of the lengths of the constituent tracks. For this to hold it is necessary to glue together consecutive express tracks: for example, the tracks in the central itinerary that lies on the real axis,  $\eta_{1/2}$ , have only a quadratic rate of length decay. To fix this, we introduce:

**Definition 5.1.** The *reduced decomposition* of an itinerary  $\eta$  is the unique decomposition  $\eta = \gamma_1 + \delta_1 + \dots$  where each  $\gamma_i$  is a concatenation of express tracks and is followed by a single peripheral track  $\delta_i$ .

**Proposition 5.2.** Let  $z \in \mathcal{J}$ , and let  $\eta_z = \gamma_1 + \delta_1 + \dots$  be the reduced decomposition of its itinerary. Then  $\text{Length}(\gamma_k) \lesssim \theta^k$  and  $\text{Length}(\delta_k) \lesssim \theta^k$  for some  $\theta < 1$ . In particular,  $\text{Length}(\eta_z) < \infty$  and all points  $z \in \mathcal{J}$  are rectifiably accessible.

For the proof, let  $\mathcal{U}_{-1}$  be the Jordan domain enclosed by the unit circle, the rightmost itinerary starting from the pre-central station and the leftmost one. See Figure 4. This domain is constructed so that it contains all itineraries that start at the station  $s_{1,1} = \psi(-1/2)$ , the preimage of the central station under  $f$ . Its crucial property is:

**Lemma 5.3.** Let  $\gamma = \gamma_1 + \delta_1 + \dots$  be the reduced decomposition of an itinerary  $\gamma$ . Then for every  $k > 1$ , there exist  $k - 1$  iterates  $n_1 < \dots < n_{k-1}$  such that  $f^{\circ n_i}(\gamma_k) \subset \mathcal{U}_{-1}$ .

*Proof.* Every station  $s \notin (0, \infty)$  has a first iterate  $f^{\circ n_s}(s)$  lying on the negative real axis  $(-\infty, 0)$ . For any  $i \in \{2, \dots, k-1\}$ , let  $s_i$  be the first station of  $\gamma_i$  and take  $n_i := n_{s_i}$ . By the definition of  $\mathcal{U}_{-1}$ , the itinerary  $f^{\circ n_i}(\gamma)$  is contained in  $\mathcal{U}_{-1}$  from the station  $f^{\circ n_i}(s_i)$  onwards, and in particular  $f^{\circ n_i}(\gamma_k) \subset \mathcal{U}_{-1}$ .  $\square$

*Proof (Proposition 5.2).* There is a uniform bound  $\|(f^{-1})'\|_{\text{hyp}} < \theta < 1$  on  $\mathcal{U}_{-1}$  with respect to the hyperbolic metric of the domain  $\hat{\mathbb{C}} \setminus \mathcal{P}$ , for both branches  $f^{-1} : \mathcal{U}_{-1} \rightarrow \mathcal{U}_{\pm i}$ . This follows from Theorem 4.1, in the slightly more general formulation of [4, Theorem 3.5], since  $\mathcal{U}_{-1}$  is compactly contained in  $\hat{\mathbb{C}} \setminus \mathcal{P}$ .

In the notation of Lemma 5.3, we then have

$$\begin{aligned}
\text{HypLength}(\gamma_k) &\leq \text{HypLength}(f^{\circ(n_1-1)}(\gamma_k)) \\
&\leq \theta \cdot \text{HypLength}(f^{\circ n_1}(\gamma_k)) \\
&\leq \dots \\
&\leq \theta^k \cdot \text{HypLength}(f^{\circ n_k}(\gamma_k)) \\
&\lesssim \theta^k.
\end{aligned} \tag{5.1}$$

As in the hyperbolic case, we infer that  $\text{Length}(\gamma_k) \lesssim \theta^k$  by the equivalence on  $B(0, R) \setminus \mathcal{P}$  of the Euclidean metric and the hyperbolic metric.  $\square$

## 5.2 Some Estimates and Notation

To estimate the length of express tracks, we introduce the notations  $s_n := s_{n,0}$  and

$$\ell_n := \text{Length}([s_n, s_{n+1}]) = s_n - s_{n+1}. \quad (5.2)$$

**Lemma 5.4.** *The lengths  $\ell_n$  satisfy:*

$$(i) \quad \frac{|p - s_n|}{\ell_n} \rightarrow \infty, \quad (5.3)$$

$$(ii) \quad \frac{\ell_n}{\ell_{n+1}} \rightarrow 1. \quad (5.4)$$

*In particular, for any  $C > 0$ , there is a sufficiently large integer  $d$  such that*

$$\ell_m + \dots + \ell_n \geq C(\ell_m + \ell_n)$$

*whenever  $|m - n| \geq d$ .*

*Proof.* Using the affine conjugacy of the map  $f$  to the map  $g : z \mapsto z^2 + z$ , which sends the parabolic fixed point  $\frac{1}{2}$  of  $f$  to 0, one can show that

$$\ell_n \asymp \frac{1}{n^2} \quad \text{and} \quad |p - s_n| \asymp \frac{1}{n}.$$

After a little arithmetic, we get (5.3) and (5.4).  $\square$

**Definition 5.5.** The *relative distance* of a curve  $\gamma$  to the post-critical set  $\mathcal{P}$  is

$$\Delta(\gamma, \mathcal{P}) = \frac{\text{dist}(\gamma, \mathcal{P})}{\min(\text{diam}(\gamma), \text{diam}(\mathcal{P}))}.$$

We say that the curve  $\gamma$  is  $\eta$ -*relatively separated* from the post-critical set if  $\Delta(\gamma, \mathcal{P}) \geq \eta$ .

If an itinerary  $\gamma$  is relatively separated from  $\mathcal{P}$ , then the preimages of  $\gamma$  under  $f$  have bounded distortion. In particular, if  $\gamma$  is a quasiconvexity certificate, then Koebe's distortion theorem implies that  $f^{-1}(\gamma)$  is also a certificate with a comparable constant.

**Lemma 5.6.** *There exists a constant  $k > 0$  such that for any pair of points  $z_1, z_2 \in \mathcal{J}$ , we have  $|f(z_1) - f(z_2)| \leq k|z_1 - z_2|$ .*

*Proof.* We have

$$|f(z_1) - f(z_2)| = \left| \int_{z_1}^{z_2} f' \right| \leq k|z_1 - z_2| \quad (5.5)$$

for  $k = \max_{z \in B} |f'(z)|$ , where  $B$  is any ball containing  $\mathcal{J}$ .  $\square$

### 5.3 Dynamics near the parabolic fixed point

The purpose of the following definition is to organize points on the Julia set  $\mathcal{J}$  according to their distance from the main cusp  $z = 1/2$  in an  $f$ -invariant way. We decompose the points of  $\mathcal{J}$  according to the first *departure*: the first time that the central itinerary makes a turn.

**Definition 5.7.** Let  $n \in \mathbb{N}$ . We define the  $n$ -th *departure set*  $I_{n, \mathbb{D}} \subset \partial \mathbb{D}^*$  to be the set of points  $\zeta \in \partial \mathbb{D}^*$  whose central itinerary  $\eta_\zeta$  starts with  $n$  express tracks, followed by a peripheral track. See Figure 6.

This decomposition is invariant under  $f_0$  in the sense that  $f_0(I_{n+1, \mathbb{D}}) = I_{n, \mathbb{D}}$ , because of the invariance of  $\eta_\zeta$ . Applying the Böttcher map  $\psi$ , we obtain a corresponding departure decomposition  $I_n = \psi(I_{n, \mathbb{D}})$  of  $\mathcal{J}$  that is invariant under  $f$ .

We now use this decomposition to analyze the case where the points  $w_1, w_2$  lie in “well-separated cusps”. Namely, suppose that

$$w_1 \in I_n, \quad w_2 \in I_m, \quad m - n > d, \quad (5.6)$$

where  $d$  is a sufficiently large integer, to be chosen later. This gives some control from below on  $|w_1 - w_2|$ . We represent the itinerary  $\eta = \eta_{w_1, w_2}$  as a concatenation

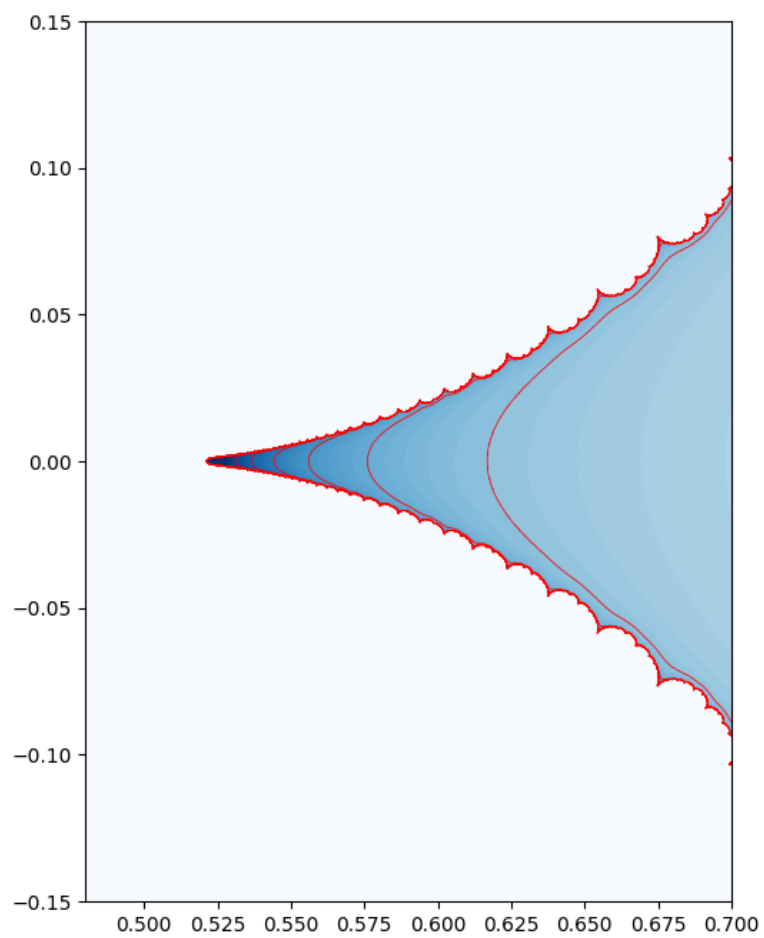


Figure 5: The Cauliflower near the parabolic point  $p = 1/2$ .

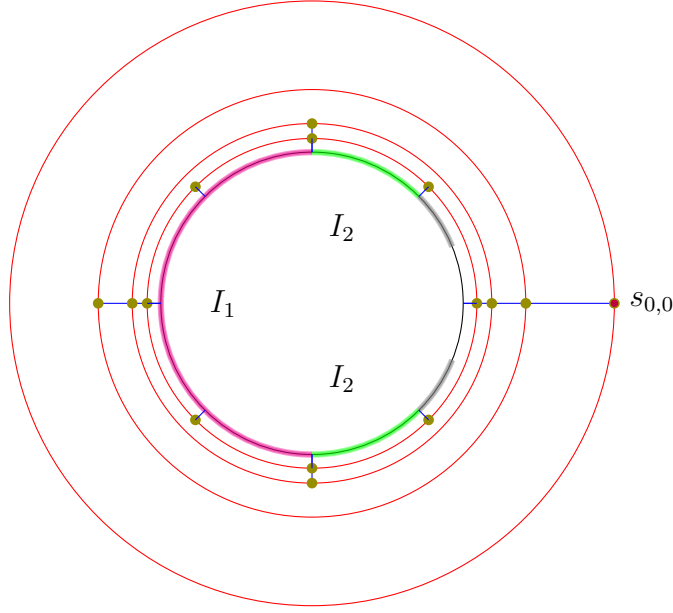


Figure 6: First few parts of the departure decomposition  $I_m$  of the circle.

of three paths: the radial segment  $\gamma_{m,n} = [s_{m,0}, s_{n,0}]$  and the two other components,  $\gamma_m$  and  $\gamma_n$ . See Figure 7 for the picture in the exterior unit disk. Thus we have

$$\text{Length}(\eta) = \text{Length}(\gamma_m) + \text{Length}(\gamma_{m,n}) + \text{Length}(\gamma_n). \quad (5.7)$$

The condition  $m - n \geq d$  prevents the line segment  $\gamma_{m,n}$  from being small in comparison to  $\gamma_m$  and  $\gamma_n$ :

**Proposition 5.8.** *There exists a sufficiently large integer  $d$  so that*

$$\text{Length}(\gamma_{m,n}) \asymp |w_1 - w_2|, \quad (5.8)$$

whenever  $m - n \geq d$ .

We henceforth fix a value of  $d$  as in the proposition.

*Proof.* We first make two elementary observations. Koebe's distortion theorem applied to the iterates of  $f^{-1}$  shows that

$$\text{Length}(\gamma_m) \leq C\ell_m, \quad (5.9)$$

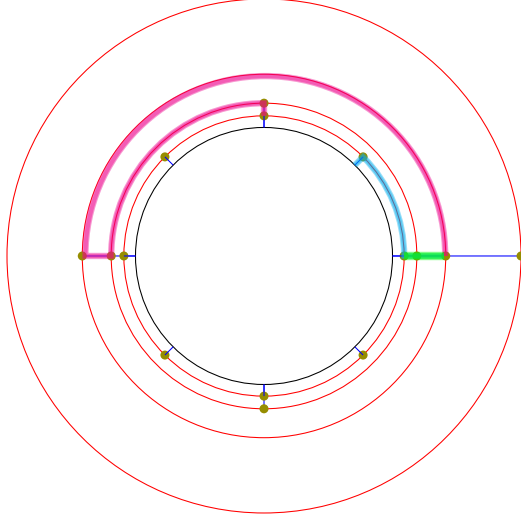


Figure 7: The three parts of an itinerary  $\eta$ . The green path is  $\gamma_{m,n}$ , the cyan and magenta are  $\gamma_m$  and  $\gamma_n$ .

for some constant  $C \geq 0$ . Notice that (5.9) holds for  $m = 1$  by Proposition 5.2, which gives a uniform bound on the length of an itinerary.

Meanwhile, by Lemma 5.4, there exists an integer  $d$  such that

$$C(\ell_m + \ell_n) \leq \frac{\text{Length}(\gamma_{m,n})}{2} \quad (5.10)$$

whenever  $m - n \geq d$ .

By the triangle inequality, we have

$$\begin{aligned} |\text{Length}(\gamma_{m,n}) - |w_1 - w_2|| &\leq \text{Length}(\gamma_m) + \text{Length}(\gamma_n) \\ &\leq \frac{\text{Length}(\gamma_{m,n})}{2}, \end{aligned}$$

which clearly implies (5.8). □

## 5.4 Quasiconvexity: three special cases

We now show that the itineraries  $\eta_{w_1, w_2}$  are certificates in three special cases. To state them, we introduce some notation.



### 5.4.1 Notation

For each  $n$ , we denote by  $\alpha_n$  the union of the two outermost tracks emanating from the station  $s_{n,0}$ . Notice that the curves  $\alpha_n$  are pairwise disjoint since this is true for their pullbacks to the exterior unit disk.

We define the constants  $C_1, C_2, \epsilon$  as follows. We first choose  $C_1 \geq 2$ , then we let  $C_2 = C_1 + d + 2$  and choose  $\epsilon > 0$  small enough so that we have

$$\text{dist}(\alpha_{C_2}, \alpha_{C_1}) \geq k\epsilon. \quad (5.11)$$

The constant  $C_2$  was chosen so that for any pair  $(m, n)$  of integers, we have at least one of the following three cases: either  $m, n$  are both greater than  $C_1$ , or both are smaller than  $C_2$ , or  $|m - n| > d$ .

### 5.4.2 Three Special Cases

In this section we treat the following special cases:

1.  $|w_1 - w_2| \geq \epsilon, \quad |m - n| < d, \quad m, n < C_2, \quad m, n \geq 2;$
2.  $|w_1 - w_2| \geq \epsilon, \quad |m - n| < d, \quad m, n > C_1;$
3.  $|w_1 - w_2| \leq k\epsilon, \quad |m - n| \geq d.$

Notice that Case 2 overlaps with Case 1. We denote the domain enclosed by  $\alpha_m, \alpha_n$  and  $\mathcal{J}$  by  $\mathcal{K}_{m,n}$ , and denote the domain enclosed by  $\mathcal{J}$  and  $\alpha_n$  by  $\mathcal{K}_n$ .

**Lemma 5.9.** *Let  $w_1 \in I_m$  and  $w_2 \in I_n$ , for  $n \geq m \geq 2$ . Then the itinerary  $\eta_{w_1, w_2}$  is contained in the domain  $\mathcal{K}_{m, n+1}$ .*

**Lemma 5.10.** *Let  $w_1, w_2 \in \mathcal{J}$ . In each of the three special cases, the itinerary  $\gamma_{w_1, w_2}$  is a quasiconvexity certificate. In Cases 1 and 2,  $\gamma_{w_1, w_2}$  is relatively separated.*

*Proof. Case 1.* In this case, the itinerary is contained in the domain  $\mathcal{K}_{2, C_2+1}$ . Since  $\text{dist}(\mathcal{K}_{2, C_2+1}, \mathcal{P}) > 0$ ,  $\gamma_{w_1, w_2}$  is  $\eta$ -relatively separated for some  $\eta > 0$ .

*Case 2.* Assuming without loss of generality that  $n \geq m$ , the itinerary is contained in  $\mathcal{K}_{m, n+1}$ . By Koebe's distortion theorem,  $\gamma_{w_1, w_2}$  is also relatively separated.

*Case 3* is the content of Proposition 5.8. □

## 5.5 Quasiconvexity: general case

We apply a stopping time argument to promote the quasiconvexity of  $\eta_{w_1, w_2}$  to the quasiconvexity of  $\eta_{z_1, z_2}$ , thereby proving the following theorem:

**Theorem 5.11.** *The domain  $\text{Exterior}(\mathcal{J})$  is quasiconvex, with the itineraries  $\eta_{z_1, z_2}$  as certificates.*

*Proof.* (Parabolic Conformal Elevator on  $\mathcal{J}$ ). Let  $(z_1, z_2)$  be a pair of points in  $\mathcal{J}$ . Repeatedly apply  $f$  to  $(z_1, z_2)$  until either of the three special cases occurs. Denote by  $w_i = f^{\circ N}(z_i)$  the resulting points. We have already proved that the itinerary  $\eta_{w_1, w_2}$  satisfies

$$\text{Length}(\eta_{w_1, w_2}) \leq A|w_1 - w_2|,$$

for some  $A > 0$ . We deduce that the original pair of points  $(z_1, z_2)$  enjoys a similar estimate,

$$\text{Length}(\eta_{z_1, z_2}) \leq C|z_1 - z_2|,$$

where  $C$  depends only on  $A$ .

In Cases 1 and 2, we are done by Lemma 5.10. In Case 3, the itinerary  $\eta_{w_1, w_2}$  is contained in  $\mathcal{K}_2$ . Let  $\mathcal{K}_{-2}$  be the preimage of  $\mathcal{K}_2$  under  $f$  that contains the negative preimage  $f^{-1}(p) = -\frac{1}{2}$  of the cusp  $p$ . As the domain  $\mathcal{K}_{-2}$  is relatively separated from  $\mathcal{P}$  and contains the curve  $f^{\circ(N-1)}(\eta_{z_1, z_2}) = \eta_{f^{-1}(w_1), f^{-1}(w_2)}$ , we may use Koebe's distortion theorem to conclude that

$$\frac{\text{Length}(\eta_{z_1, z_2})}{|z_1 - z_2|} \asymp \frac{\text{Length}(\eta_{f^{-1}(w_1), f^{-1}(w_2)})}{|f^{-1}(w_1) - f^{-1}(w_2)|} \asymp \frac{\text{Length}(\eta_{w_1, w_2})}{|w_1 - w_2|} \quad (5.12)$$

as desired.  $\square$

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