FATOU’S ASSOCIATES

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For Misha Lyubich on the occasion of his 60th birthday

Abstract. Suppose that $f$ is a transcendental entire function, $V \subseteq \mathbb{C}$ is a simply connected domain, and $U$ is a connected component of $f^{-1}(V)$. Using Riemann maps, we associate the map $f: U \to V$ to an inner function $g: \mathbb{D} \to \mathbb{D}$. It is straightforward to see that $g$ is either a finite Blaschke product, or, with an appropriate normalisation, can be taken to be an infinite Blaschke product.

We show that when the singular values of $f$ in $V$ lie away from the boundary, there is a strong relationship between singularities of $g$ and accesses to infinity in $U$. In the case where $U$ is a forward-invariant Fatou component of $f$, this leads to a very significant generalisation of earlier results on the number of singularities of the map $g$.

If $U$ is a forward-invariant Fatou component of $f$ there are currently very few examples where the relationship between the pair $(f, U)$ and the function $g$ have been calculated. We study this relationship for several well-known families of transcendental entire functions.

It is also natural to ask which finite Blaschke products can arise in this way, and we show the following: For every finite Blaschke product $g$ whose Julia set coincides with the unit circle, there exists a transcendental entire function $f$ with an invariant Fatou component such that $g$ is associated to $f$ in the above sense. Furthermore, there exists a single transcendental entire function $f$ with the property that any finite Blaschke product can be arbitrarily closely approximated by an inner function associated to the restriction of $f$ to a wandering domain.

1. Introduction

Although much of this paper concerns dynamics, we begin in a more general setting. Suppose that $f$ is a transcendental entire function, that $V \subseteq \mathbb{C}$ is a simply connected domain, and that $U$ is a connected component of $f^{-1}(V)$; note that $U$ is simply connected. We can let $\phi: \mathbb{D} \to U$ and $\psi: \mathbb{D} \to V$ be Riemann maps, and then set $g := \psi^{-1} \circ f \circ \phi$; see Figure 1. We begin with a result that summarises the properties of the map $g$. This is not entirely new but to the best of our knowledge it has not been stated in this generality before. Here an inner function is a holomorphic self-map of $\mathbb{D}$ for which radial limits exist at almost all points of the unit circle, and belong to the unit circle. A particular class of inner

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functions is the class of Blaschke products. These are functions of the form
\begin{equation}
B(z) := e^{i\theta} \prod_{n=1}^{d} \frac{|a_n|}{a_n} \frac{a_n - z}{1 - \overline{a_n}z},
\end{equation}
where \( \theta \in \mathbb{R} \), \( d \in \mathbb{N} \cup \{\infty\} \), and \((a_n)_{1 \leq n \leq d}\) is a sequence of points of \( \mathbb{D} \), which satisfies the condition \( \sum (1 - |a_n|) < \infty \). When \( a_n = 0 \) we interpret the term in the infinite product simply as \( z \). If \( d \) is finite then \( B \) is called a finite Blaschke product of degree \( d \), and otherwise it is an infinite Blaschke product.

Proposition 1.1. Suppose that \( f \) is a transcendental entire function, that \( V \subset \subset \mathbb{C} \) is a simply connected domain, and that \( U \) is a connected component of \( f^{-1}(V) \). Let \( \phi : \mathbb{D} \to U \) and \( \psi : \mathbb{D} \to V \) be conformal, and set \( g := \psi^{-1} \circ f \circ \phi \). Then \( g \) is an inner function, which, for an appropriate choice of \( \phi \) and \( \psi \), can be taken to be a Blaschke product. More precisely, exactly one of the following conditions holds.

(a) Finite valence: \( g \) is a finite Blaschke product of degree \( d \), for some \( d \in \mathbb{N} \), and \( f|_U \) is of constant finite valence \( d \).

(b) Infinite valence: \( g \) is an infinite Blaschke product, and \( U \cap f^{-1}(z) \) is infinite for all \( z \in V \) with at most one exception.

In the setting of Proposition 1.1 we say that \( g \) is an inner function associated to \( f|_U \). Such inner functions have been considered before; see, for example, [Bis15, p.5].

Remark. Note that Proposition 1.1 implies that there are many inner functions which cannot be associated to a transcendental entire function in the sense of this paper. For example, see [Ste78], if \( A \) is any closed subset of \( \mathbb{D} \), of (logarithmic) capacity zero, then there is an inner function that omits all the points of \( A \).

1Sometimes, the term “Blaschke product” is used more generally for a function of the form (1.1) where some \( a_n \) may also have \( |a_n| > 1 \), so that \( B \) has poles in \( \mathbb{D} \). These are not inner functions, and we will not consider them in this paper.
In our first main result, which we will use to significantly generalise earlier results in a dynamical setting, we are interested in the singularities of the associated inner function; a point \( \zeta \in \partial \mathbb{D} \) is called a singularity of (an inner function) \( g \), if \( g \) cannot be extended holomorphically to any neighbourhood of \( \zeta \) in \( \mathbb{C} \). For a transcendental entire function \( f \), we denote by \( S(f) \) the set of singular values of \( f \); in other words, the closure of the set of critical and finite asymptotic values of \( f \). Our result is as follows.

**Theorem 1.2.** Suppose that \( f \) is a transcendental entire function, that \( V \subseteq \mathbb{C} \) is simply connected, and that \( U \) is a component of \( f^{-1}(V) \) such that \( f : U \rightarrow V \) is of infinite valence. Suppose that there is a bounded Jordan domain \( D \), containing \( S(f) \cap V \), and with \( \overline{D} \subset V \). Then the singularities of an associated inner function \( g \) are in order-preserving one-to-one correspondence with the accesses to infinity in \( U \cap f^{-1}(D) \). In particular, the number of singularities of \( g \) is equal to the number of components of \( U \setminus f^{-1}(\overline{D}) \).

**Remark.**

(a) An access to infinity in \( U \cap f^{-1}(D) \) is a homotopy class of curves to infinity in \( U \); see Section 3.

(b) By the final statement, we mean that the number of singularities and the number of components are either both infinite, or both finite and equal. We caution that, when infinite, the number of singularities may be uncountable, while the number of components of \( U \setminus f^{-1}(\overline{D}) \) is always countable.

(c) In the case of finite valence, it follows from Proposition 1.1 that any associated inner product is a finite Blaschke product, and has no singularities.

We now consider associated inner functions in a dynamical setting. Let \( f \) be a transcendental entire function, and denote by \( f^n \) the \( n \)th iterate of \( f \). The set of points for which the set of iterates \( \{f^n\}_{n \in \mathbb{N}} \) form a normal family in some neighbourhood is the Fatou set \( F(f) \), and its complement in the complex plane is the Julia set \( J(f) \). The Fatou set is open, and so consists of connected components which are called Fatou components. For an introduction to the properties of these sets see, for example, [Ber93].

In the case that \( U \) is a simply-connected Fatou component, and \( V \) is the Fatou component containing \( f(U) \), then the conditions we discussed earlier all hold, and we can associate an inner function to \( f|_U \). A case of particular interest is when the Fatou component \( U \) is forward invariant, in other words such that \( f(U) \subset U \). Note that it is well known that forward-invariant Fatou components are necessarily simply connected. In this case we have that \( U = V \), we can set \( \psi = \phi \), and the dynamics of \( f \) on \( U \) is conjugate to the dynamics on \( \mathbb{D} \) of the function \( g := \phi^{-1} \circ f \circ \phi \). Moreover, \( g \) is unique in this respect, up to a conformal conjugacy. In this case we say that \( g \) is an inner function dynamically associated to \( f|_U \). Many authors have used inner functions to study the iteration of transcendental entire functions in this setting; see, for example, [DG87], [Kis98], [BD99], [FH06], [Bar07], [BK07], [BF01], [Bar08], [EFJS19].

**Theorem 1.2** has the following corollary, which is a significant generalisation of the main result of [EFJS19]. Here we consider the class \( \mathcal{B} \) of transcendental entire functions for which \( S(f) \) is bounded, and for a function \( f \in \mathcal{B} \) a tract is a
component of $f^{-1}(\mathbb{C} \setminus \overline{D'})$ where $D'$ is a bounded Jordan domain containing $S(f)$. It is well-known that the number of tracts is independent of the choice of $D'$.

**Corollary 1.3.** Suppose that $f \in \mathcal{B}$, and that $S(f) \subset F(f)$. Suppose also that $U$ is an unbounded forward-invariant Fatou component of $f$. Then the number of singularities of a dynamically associated inner function is at most equal to the number of tracts of $f$.

This generalises [EFJS19, Theorem 1.5], in which the condition that $S(f)$ is a compact subset of the Fatou set was replaced by the condition that the *postsingular set* defined by

$$\mathcal{P}(f) := \bigcup_{j \geq 0} f^j(S(f)),$$

is a compact subset of the Fatou set; such functions are called *hyperbolic*.

Lyubich (personal communication) has asked which inner functions $G$ arise as dynamically associated inner functions. Few authors have explicitly calculated $g$ for given functions $f$. Indeed, we are aware of only two examples in the literature. First, Devaney and Goldberg [DG87] considered the Julia set of $f_\lambda(z) := \lambda e^z$ for values of $\lambda$ such that $f$ has a completely invariant attracting basin $U$. They showed that these functions have a dynamically associated inner function of the form

$$(1.2) \quad g(z) := \exp \left( i \frac{\mu + \bar{\mu}z}{1 + z} \right),$$

where $\mu$ lies in the upper half-plane $\mathbb{H}$, and depends on $\lambda$. Note that $g$ is not an infinite Blaschke product – indeed, the proof technique used in [DG87] depends on this fact – but is conjugate to one. However, Devaney and Goldberg did not determine which values of $\mu$ are realised.

The result of Devaney and Goldberg was generalised later by Schleicher. He considered the case that $f_\lambda$ has an attracting *periodic* point; in this case $f_\lambda$ is *hyperbolic*. He observes that the associated inner functions can always be chosen to take a certain form, which is equivalent to (1.2); see [Sch99, Lemmas III 4.2, III 4.3] for details.

Second, Baker and Domínguez [BD99] showed that the map $f(z) := z + e^{-z}$ has an invariant Fatou component with the dynamically associated Blaschke product

$$(1.3) \quad g(z) := \frac{3z^2 + 1}{3 + z^2},$$

and it is easy to see how to write $g$ in the form (1.1).

In view of this, perhaps unexpected, dearth of specific examples, our next goal in this paper is to find classes of transcendental entire functions, $\mathcal{F}$, and classes of inner functions, $\mathcal{G}$, with the following properties;

(I) Each $f \in \mathcal{F}$ has a forward-invariant Fatou component $U$;

(II) For each $f \in \mathcal{F}$ there is an inner function $g \in \mathcal{G}$ dynamically associated to $f$;

(III) For each $g \in \mathcal{G}$ there is an $f \in \mathcal{F}$ such that $g$ is dynamically associated to $f$. 

We begin with a result of this form for finite Blaschke products. Note that, if an inner function $g : D \to D$ is dynamically associated to an invariant attracting or parabolic Fatou component of an entire function, then $g$ either has an attracting fixed point in $D$, or a triple fixed point on $S^1 = \partial D$. Equivalently, $J(g) = S^1$ [Fle15].

**Theorem 1.4.** Let $\mathcal{F}$ consist of all entire functions having a forward-invariant attracting or parabolic Fatou component $U$ that is a bounded Jordan domain. Let $\mathcal{G}$ be the connectedness locus of finite Blaschke products; that is, $\mathcal{G}$ consist of all finite Blaschke products of degree $d \geq 2$ with $J(g) = S^1$. Then (I), (II) and (III) hold.

Observe that (I) and (II) hold by assumption and Proposition 1.1, so the main content of the theorem is showing the existence of an entire function realising a prescribed Blaschke product as its dynamically associated inner function. This will be achieved by quasiconformal surgery.

Next, we give a complete description of dynamical inner functions for exponential maps with attracting fixed points, thus completing the work of Devaney and Goldberg. Similarly as in [Sch99], we find it convenient to change coordinates from the unit disc to the upper half-plane and consider inner functions of the upper half-plane associated to $f|_U$. Compare also [Bar08]. We use the family of functions

\[(1.4) \quad g_{a,b} : \mathbb{H} \to \mathbb{H} := a \tan(z) + b, \quad a > 0, b \in (-\pi/2, \pi/2].\]

It is easy to check that $g_{a,b}$ is conjugate to $g_\mu$ as in (1.2) for $\mu = (b + ai)/2$. Thus the following result also gives a complete description of the set of $\mu$ for which $g_\mu$ arises as an inner function of an exponential map.

**Theorem 1.5.** Set

$$\mathcal{F} := \{f_\lambda : f_\lambda \text{ has an attracting fixed point}\} = \{f_{\mu e^{-\nu}} : \mu \in \mathbb{D} \setminus \{0\}\},$$

where $f_\lambda(z) = \lambda e^z$. Also let

$$\mathcal{G} := \{g_{a,b} : g_{a,b} \text{ has an attracting fixed point in } D\}$$

$$= \{g_{a,b} : a > 1 \text{ or } |b| > \arccos(\sqrt{a}) - \sqrt{a} \cdot \sqrt{1-a}\}.$$

Then $\mathcal{F}$ and $\mathcal{G}$ satisfy (I), (II) and (III). More precisely, for every $f_\lambda \in \mathcal{F}$, the family $\mathcal{G}$ contains exactly one dynamically associated inner function of $f$, and vice versa.

As in Schleicher’s work, our theorem applies also to iterates of exponential maps. Indeed, more generally the following is true.

**Theorem 1.6.** Let $\mathcal{G}$ be as above, and let $f$ be a transcendental entire function, and suppose that $U$ is a basin of attraction of period $n$ for $f$. If the cycle of $U$ contains only one singular value of $f$, and $f^n : U \to U$ is of infinite valence, then $\mathcal{G}$ contains exactly one dynamically associated inner function of $f^n$ on $U$.

While [DG87] and [Sch99, Section III.4] only treated attracting dynamics, we can also consider parabolic basins, thus completing the description of associated inner functions for periodic Fatou components of exponential maps.
Theorem 1.7. Let \( f \) be a transcendental entire function, and suppose that \( U \) is a parabolic basin of period \( n \) for \( f \). If the cycle of \( U \) contains only one singular value of \( f \), and \( f^n : U \to U \) is of infinite valence, then \( \tan : \mathbb{H} \to \mathbb{H} \) is a dynamically associated inner function for \( f^n \) on \( U \).

We are able to give a similar description of dynamically associated inner functions in cases where \( f^n : U \to U \) takes some value only finitely many times, see Theorem 6.1. In particular, this applies to many functions of the form

\[ f(z) := \lambda P(z)e^{Q(z)}; \]

see Corollary 6.2.

The case of Fatou components containing infinitely many critical points is more complicated. We begin with the following detailed example.

Theorem 1.8. There is a homeomorphism \( \psi : (0, 1) \to (1, \infty) \) with the following property. Let \( \mathcal{F} \) be the family of transcendental entire functions

\[ f_\lambda(z) := \lambda \sin z, \quad \text{for } \lambda \in (0, 1). \]

For \( \mu > 1 \) let

\[ a_n = a_n(\mu) := \frac{\mu^n - 1}{\mu^n + 1}, \quad \text{for } n \in \mathbb{N}, \]

and let \( \mathcal{G} \) be the family of infinite Blaschke products

\[ g_\mu(z) := z \prod_{n=1}^{\infty} \frac{a_n^2 - z^2}{1 - a_n^2 z^2}. \]

Then (I), (II) and (III) hold for these families, with \( \mu = \psi(\lambda) \).

Remark. The proof of Theorem 1.8 makes strong use of symmetries of the Julia sets of the functions involved. It is not easy to see, therefore, how one might extend these results to wider families such as \( f(z) := \lambda e^z \), with \( \lambda \) close to zero but not positive.

Let \( g \) be an inner function dynamically associated to an invariant Fatou component \( U \) of infinite valence for a transcendental entire function \( f \). Let \( A \) denote the set of singularities of \( g \). By the Schwarz reflection principle, \( g \) extends to a meromorphic function on \( \hat{\mathbb{C}} \setminus A \), so we can think of \( g \) as a global complex dynamical system. As mentioned above, if \( U \) is an attracting or parabolic basin, we have \( J(g) = S^1 \); see [Kis98, Lemma 2], [BD99, Lemmas 8 and 9] and [Bar08, Theorem 2.24]. Here the Julia set \( J(g) \) consists of those points of \( S^1 \) that have no neighbourhood on which the iterates of \( g \) are defined and normal [BD99, Section 3].

If \( \#A = 1 \), then \( g \) is (up to conformal conjugacy) a transcendental meromorphic function. When \( A \) is countable, \( g \) belongs to a class of functions for which the theory of complex dynamics was developed by Bolsch [Bol99]. Similarly, if \( f \) has only finitely many singular values in the Fatou component \( U \), then \( g \) is a finite-type map in the sense of Epstein [Eps93]; see also [Rem09, CE18]. In particular, inner functions allow us to construct many examples of functions in these classes for which the Julia set is a circle. A larger class of holomorphic functions for which Fatou-Julia iteration theory has been extended is Epstein’s theory of Ahlforis islands maps; see [Rem09, RR12], and also [BDH01] for the case where \( A \neq S^1 \).
It would be interesting to investigate when the inner function $g$ associated to $f$ satisfies this Ahlfors islands condition.

For families of entire functions with a finite number of singular values, it is plausible that the preceding observation about finite-type maps, together with surgery techniques similar to Theorem 1.4 can lead to a description of the associated inner functions. On the other hand, it appears to be very difficult to develop general principles for inner functions associated to Fatou components where the singular values are allowed to accumulate on the boundary. It is perhaps surprising that we can nonetheless give a very precise description in one particular case.

**Theorem 1.9.** Let $F$ be the family of transcendental entire functions

$$f_\lambda(z) := \lambda + z + e^{-z}, \quad \text{for } \lambda > 0.$$  

Let $G$ be the family of maps $g_\lambda: \mathbb{H} \to \mathbb{H}$

$$g_\lambda(z) := z - \lambda \cot z, \quad \text{for } \lambda > 0.$$  

Then (I), (II) and (III) hold for these families, with $g_\lambda$ being associated to the restriction of $f_\lambda$ to its single Fatou component.

**Remarks.**

1. Note that in the proof of this result we make strong use of symmetries of the Julia sets of the functions involved. It is not easy to see, therefore, how one might extend these results to wider families where $\lambda$ is not real and positive.

2. The map $g_\lambda$ is conjugate to the map $h_\lambda(z) := z + \lambda \tan z$ via the conjugation $z \mapsto \pi/2 - z$. We prefer the choice of $g_\lambda$ as it makes the proof slightly simpler. Note that the dynamics of the map $h_\lambda$ was studied in [BFJK17].

3. The dynamics of the family $F$ was studied in [Evd16], with the parametrisation

$$h(z) := z + a + be^{cz}, \quad \text{for } b \neq 0, \quad ac < 0.$$  

(Up to conjugations, this is the same as the family $F$.)

To conclude, let us return to the case of inner functions associated to $f: U \to V$ where $U \neq V$, and in particular to the case where $U$ and $V$ are simply-connected wandering domains of a transcendental entire function $f$. Similarly as in Theorem 1.4 we show that every finite Blaschke product may arise in this manner.

**Theorem 1.10.** Let $B: \mathbb{D} \to \mathbb{D}$ be a Blaschke product of degree $d$, with $2 \leq d < \infty$. Then there is a transcendental entire function $f$ having wandering domains $U$ and $V = f(U)$ which are bounded Jordan domains and such that $g$ is an inner function associated to $f|_U$.

Moreover, using approximation theory we can construct a single inner function $f$ whose associated inner functions approximate any desired Blaschke product:

**Theorem 1.11.** There is a transcendental entire function $f$ having a simply-connected wandering domain $U$ with the following property. Given a finite Blaschke product $B$ and $\epsilon > 0$, there is $n \geq 0$ and a Blaschke product $g$ associated to $f: f^n(U) \to f^{n+1}(U)$, such that the following both hold.

1. $|g(z) - B(z)| < \epsilon$, for $z \in \mathbb{D}$. 

2. $f^n(U)$ is contained in $\mathbb{D}$.

3. $f^{n+1}(U)$ is contained in the interior of $\mathbb{D}$.

4. $f^{n+1}(U)$ is contained in $\mathbb{D}$.

5. $f^n(U)$ is contained in the complement of $\mathbb{D}$.

6. $f^{n+1}(U)$ is contained in the complement of $\mathbb{D}$.
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2. Proof of Proposition 1.1

In this section, our goal is to prove Proposition 1.1. To do this, we first need a little background on inner functions.

It is well-known that it is possible to factorise inner functions in a canonical way. First we define a singular inner function as a function of the form

\[ S(z) := \exp \left( - \int \frac{e^{i\theta} + z}{e^{i\theta} - z} \, d\mu(\theta) \right), \]

for some positive and singular measure \( \mu \). We then have the following; see, for example, [Gar07, p.72] together with [Gar07, Theorem 6.4].

**Theorem 2.1.** If \( g : \mathbb{D} \to \mathbb{D} \) is an inner function, then there is a Blaschke product \( B \) and a singular inner function \( S \) such that \( g = B \cdot S \). Moreover, for all \( \zeta \in \mathbb{D} \), except possibly for a set of capacity zero, the function

\[ g_\zeta(z) := \frac{g(z) - \zeta}{1 - \overline{\zeta}g(z)}, \]

is a Blaschke product.

We will also use the following, which is a version of [Hei57, Theorem 4'].

**Theorem 2.2.** Suppose that \( f \) is a transcendental entire function, that \( V \) is a domain, and that \( U \) is a component of \( f^{-1}(V) \). Then exactly one of the following holds.

(i) there exists \( n \in \mathbb{N} \) such that \( f \) assumes in \( U \) every value of \( V \) exactly \( n \) times.

(ii) \( f \) assumes in \( U \) every value of \( V \) infinitely often with at most one exception.

We are now able to prove Proposition 1.1.

**Proof of Proposition 1.1** That \( g \) is an inner function was shown in [EFJS19], in a much less general context, and we repeat the argument for completeness. Suppose that \( g \) was not inner. By Fatou’s Theorem, there would exist a set \( E \subset \partial \mathbb{D} \), of positive measure with respect to \( \mathbb{D} \), on which \( g \) had non-tangential limits of modulus strictly less than one, and on which \( \phi \) had well-defined limits. It would follow that

\[ \phi(E \setminus \phi^{-1}(\{\infty\})) \subset \partial U \]

was a set of positive harmonic measure with respect to \( U \) that was mapped by \( f \) into \( V \). This is a contradiction, since \( f(\partial U) \subset \partial V \).

To see that \( g \) can be taken to be a Blaschke product, choose \( \zeta \in \mathbb{D} \) such that, by the second part of Theorem 2.1, the function \( g_\zeta(z) = \omega(g(z)) \) is a Blaschke product, where

\[ \omega(z) := \frac{z - \zeta}{1 - \overline{\zeta}z}. \]
Set $\tilde{\phi} := \phi \circ \omega^{-1}$ and $\tilde{\psi} := \psi \circ \omega^{-1}$, and so
$$\tilde{g} := \tilde{\psi}^{-1} \circ f \circ \tilde{\phi} = \omega \circ \psi^{-1} \circ f \circ \phi \circ \omega^{-1} = g \circ \omega^{-1},$$
is a Blaschke product which is associated to $f$.

If $g$ is a finite Blaschke product, of degree $d$ say, then it is easy to see that each point of $D$ has exactly $d$ preimages up to multiplicity. The statement for $f$ is then immediate, and this gives the case (a).

Otherwise, $g$ is an infinite Blaschke product. In particular $g^{-1}(0)$ is infinite. It follows by Theorem 2.2 that $g^{-1}(\zeta)$ is infinite for all $\zeta \in D$ except at most one point.

3. Singularities of inner functions

The main goal of this section is to prove Theorem 1.2. Recall that by an access to infinity within a domain $U$ we mean a homotopy class of curves tending to infinity within $U$. Any collection of pairwise disjoint curves to infinity comes equipped with a natural cyclic order, which records how these curves are ordered around $\infty$ according to positive orientation. If $U$ is simply-connected, this in turn gives rise to a natural cyclic order on accesses to infinity in $U$. Carathéodory’s theory of prime ends, see e.g. [Pom92a, Chapter 2], provides a natural correspondence between accesses to infinity in $U$ and the set of points on the unit circle where a Riemann map has radial limit $\infty$. Indeed, it follows from the definition that accesses to infinity are in one-to-one correspondence with the prime ends represented by a sequence of cross-cuts tending to infinity, and therefore the following result follows from [Pom92a, Corollary 2.17]. Compare [BFJK17, Correspondence Theorem] for details.

Proposition 3.1. Let $U \subset \mathbb{C}$ be a simply-connected domain, and let $\phi: \mathbb{D} \to U$ be a conformal isomorphism. Set
\begin{equation}
(3.1) \Theta := \{ \zeta \in S^1 : \lim_{t \uparrow 1} \phi(t \zeta) = \infty \}
\end{equation}
For $\zeta \in \Theta$, let $\alpha(\zeta)$ denote the access to infinity in $U$ represented by $\phi([0,1) \cdot \zeta)$. Then $\alpha$ is a cyclic-order-preserving bijection between $\Theta$ and the set of accesses to infinity in $U$.

Moreover, if $\gamma: [0,\infty) \to U$ is any curve to infinity in $U$ representing an access $[\gamma]$, then $f^{-1}(\gamma(t)) \to \alpha^{-1}([\gamma])$ as $t \to \infty$.

Observe that Proposition 3.1 could also be used as a definition of accesses to infinity in $U$ and their cyclic order. The proof of Theorem 1.2 uses some ideas that were also used in the proof of [EFJS19, Theorem 1.1]; for the reader’s convenience, we shall give a largely self-contained account, relying only on classical results on the boundary behaviour of univalent functions.

Proof of Theorem 1.2. Recall that $f$ is a transcendental entire function, $V \subsetneq \mathbb{C}$ is a simply connected domain, and $U$ is a component of $f^{-1}(V)$ such that $f: U \to V$ has infinite valence. Finally $D$ is a bounded Jordan domain containing $S(f) \cap V$, such that $\overline{D} \subset V$. Set $D_0 := f^{-1}(D) \cap U$. Then $f: U \setminus \overline{D_0} \to V \setminus \overline{D}$ is a covering map. Since $V \setminus \overline{D}$ is an annulus, and the map has infinite degree, it follows that $f$ is a universal covering when restricted to any connected component $T$ of $U \setminus \overline{D_0}$, and
that consequently $D_0$ is connected, simply connected and unbounded. Compare Proposition 2.9 for details.

Let $T$ denote the set of components of $U \setminus \overline{D_0}$. With a slight abuse of terminology we call these the tracts in $U$. Let $T \in \mathcal{T}$. By the above, exactly one of the boundary components of $T$, $\Gamma(T)$ say, is a preimage of $\partial D$, and so is an arc, tending to infinity in both directions, which is mapped as a universal covering map.

Now consider Riemann maps $\phi: \mathbb{D} \to U$ and $\psi: \mathbb{D} \to V$ and an inner function $g := \psi^{-1} \circ f \circ \phi$ associated to $f|_U$. Let $\Theta \subset S^1$ be defined as in (3.1), and let $\Theta' \subset \Theta$ denote the subset corresponding to accesses to infinity in $D_0$. Note that, by the F. and M. Riesz theorem [Pom92a Theorem 1.7], the set $\Theta$ has zero Lebesgue measure and is therefore totally disconnected. Let $X \subset S^1$ denote the set of singularities of $g$; note that $X$ is a compact subset of $S^1$. We wish to show that $X = \Theta'$, which will be achieved by studying the structure of

$$W_0 := \phi^{-1}(D_0) = g^{-1}(W),$$

where $W = \psi^{-1}(D)$. The set $\partial W_0 \cap \mathbb{D} = g^{-1}(\partial W)$ consists of the countably many curves $\gamma(T) := \phi^{-1}(\partial T)$ for $T \in \mathcal{T}$. Each $\gamma(T)$ is an arc tending to $S^1$ in both directions. By Proposition 3.1, $\gamma(T)$ in fact has two end-points $a(T), b(T) \in \Theta'$ on the unit circle. We may choose the labelling such that $\gamma(T)$ separates the arc $I(T) := (a(T), b(T))$ of $S^1$, understood in positive orientation, from $W_0$. This implies that

$$\partial W_0 = \bigcup_{T \in \mathcal{T}} \gamma(T) \cup \left( S^1 \setminus \bigcup_{T \in \mathcal{T}} I(T) \right).$$

Claim 1. $a(T), b(T) \in X$ for all $T \in \mathcal{T}$.

Proof. The restriction $g: \gamma(T) \to \partial W$ is a universal covering. In particular, every point of $\partial W$ has infinitely many preimages near $a(T)$ and $b(T)$, and these points must be singularities of $g$. \hfill $\triangle$

Claim 2. The map $g$ extends continuously to each $I(T)$ as an analytic universal covering $g: I(T) \to S^1$. In particular, $I(T) \cap X = \emptyset$.

Proof. The map $g: \phi^{-1}(T) \to \mathbb{D} \setminus W$ is a universal covering map. Since $\mathbb{D} \setminus W$ is an annulus, the restriction is equivalent, up to analytic changes of coordinate in domain and range, to the restriction of the complex exponential map to a horizontal strip $S$, with $a(T)$ and $b(T)$ corresponding to $-\infty$ and $+\infty$ on the boundary of $S$. The conformal isomorphism between $\phi^{-1}(T)$ and $S$ extends continuously to $I(T)$, and thus $g$ extends continuously to $I(T)$ as a universal covering of $S^1$. By the Schwarz reflection principle, the extension is analytic. \hfill $\triangle$

Claim 3. $W_0$ is a Jordan domain, and $\Theta' = \partial W_0 \cap S^1 = S^1 \setminus \bigcup_T I(T)$.

Proof. Define $\rho: S^1 \to \partial W_0$ as follows. On each $I(T)$, the map is a homeomorphism $\rho|_{I(T)} \to \gamma(T)$, fixing the endpoints $a(T)$ and $b(T)$. Outside these intervals, i.e. on $\partial W_0 \cap S^1$, $\rho$ agrees with the identity. (Note that, by Claim 2, each $I(T)$ is indeed a non-degenerate interval, so such $\rho$ does indeed exist.)

Clearly $\rho$ is injective; furthermore it is surjective by (3.2), and continuous at any point of $\bigcup_T I(T)$ by definition. So suppose that $\zeta \in \partial W_0 \cap S^1$, and let $\varepsilon > 0$. By
the Carathéodory prime ends correspondence, there is a cross-cut $C$ of $\mathbb{D}$ contained
in the Euclidean disc $D(\zeta, \varepsilon)$ of radius $\varepsilon$ around $\zeta$, such that $C$ separates $\zeta$ from
0 and $\phi(C)$ is a cross-cut of $U$ with finite endpoints [Pom92a, Theorem 2.15].
Since $\partial D_0 \cap \mathbb{C}$ is locally an arc, and $\phi(C)$ is bounded, $\partial T$ intersects $\phi(C)$ only for
finitely many $T$. (Compare [BRG17, Lemma 2.1].) Hence, with at most finitely many exceptions, either the interval $(a(T), b(T))$ has distance at least $\varepsilon$ from $\zeta$, or $\gamma(T)$ is contained in $D(\zeta, \varepsilon)$. It follows easily that $\rho$ is indeed continuous, and
therefore a homeomorphism. We have proved that $W$ is a Jordan domain.

Clearly no $I(T)$ intersects $\Theta'$, and hence $\Theta' \subset \partial W_0 \cap S^1$. On the other hand,
every $\zeta \in \partial W_0 \cap S^1$ is accessible from $W_0$ by the first part of the claim. If $\gamma \subset W$
is a curve tending to $\zeta$, then $\phi(\zeta)$ must tend to $\hat{\partial}U \cap \hat{\partial}D_0 = \{0\}$ (where $\hat{\partial}$
denotes the boundary in the Riemann sphere $\hat{\mathbb{C}}$). Hence $\zeta \in \Theta'$ by Proposition 3.1 as
required.

Since $\Theta' \subset \Theta$ is totally disconnected, it follows from Claim 3 that the set
$\bigcup_a \{a(T), b(T)\}$ of endpoints of the intervals $I(T)$ is dense in $\Theta'$. In particular,
by Claim 1, $\Theta' \subset X$, and $X \subset \Theta'$ by Claims 2 and 3. We have established that
$X = \Theta'$.

By Proposition 3.1, the set $\Theta'$ is in one-to-one cyclic-order-preserving correspon-
dence with the set of accesses to infinity in $D_0$. Thus we have proved the first claim
of the theorem. Moreover, clearly $\Theta' = S^1 \setminus \bigcup_T I(T)$ is finite if and only if $T$
is finite. If this is the case, the map $T \mapsto a(T)$ defines a bijection between $T$ and $\Theta'$.
This completes the proof.

Proof of Corollary 1.3. Suppose that $f \in \mathcal{B}$, that $S(f) \subset F(f)$, and that $U$ is an
unbounded forward-invariant Fatou component of $f$. Choose a point $w \in U$, and
let $D \subset U$ be a hyperbolic disc, centred at $w$, of sufficiently large hyperbolic radius
that $S(f) \cap U \subset D$; this is possible since $S(f)$ is compact and does not meet $\partial U$.

It follows from Theorem 1.2 that the number of singularities of an associated
inner function is equal to the number of components of $U \setminus f^{-1}(\overline{D})$. Since $\overline{D} \subset U$,
each component of $U \setminus f^{-1}(\overline{D})$ is contained in exactly one component of $\mathbb{C} \setminus (U \cap f^{-1}(\overline{D}))$, so it suffices to count the components of this latter set.

Now let $D' \supset D$ be a bounded Jordan domain containing $S(f)$, so that the
tracts of $f$ are the components of $\mathbb{C} \setminus f^{-1}(\overline{D'})$. Since $D' \supset D$, no tract can meet
more than one component of $\mathbb{C} \setminus (U \cap f^{-1}(\overline{D}))$. However, each component of
$\mathbb{C} \setminus (U \cap f^{-1}(\overline{D}))$ meets at least one tract. This completes the proof.

4. Bounded-degree inner functions

In this section, we prove Theorems 1.4 and 1.10. The results are proved by a
standard type of quasiconformal surgery [BF14, Section 4.2], which is analogous to
the well-known proof of the straightening theorem for polynomial-like mappings
[DH85]. Throughout this section, and only in this section, we shall use without
comment the standard notions and techniques of quasiconformal surgery, as
explained for example in [BF14].

We begin with Theorem 1.10, where the surgery takes a particularly simple
form. We shall require the following result, which establishes the existence of a
suitable function on which to perform the surgery.
**Proposition 4.1.** Let $d \geq 2$. Then there exists an entire function $h$ having a simply-connected wandering domain $W$ such that, for all $n \geq 0$, $h^n(W)$ is a Jordan domain and $h : f^n(W) \to f^{n+1}(W)$ is a proper map of degree $d$.

**Proof.** We use the well-known method of obtaining wandering domains by lifting invariant components of a self-map of $\mathbb{C}^* = \mathbb{C} \setminus \{0\}$. Compare \cite{Hermes84} p. 106 and \cite{Sul85} p. 414 for early examples, and \cite{BEF19} p. 3 for a general description of this method.

Define

$$p(z) := 2 \cdot \sum_{j=1}^{d-1} \binom{d-1}{j} \cdot \frac{z^{j+1}}{j+1},$$

and

$$c := \exp(-p(-1)), \quad f(z) := -c \cdot z^2 \cdot \exp(p(z)).$$

Then $p'(z) = 2 \cdot ((z + 1)^{d-1} - 1)/z$, and so $f$ is a transcendental entire function with $f'(z) = -c \cdot \exp(p(z)) \cdot (2z + z^2 p'(z)) = -2c \cdot \exp(p(z)) \cdot z \cdot (z + 1)^{d-1}$. Hence $f$ has super-attracting fixed points at 0 and $-1$, and no other singular values. Let $U$ be the Fatou component of $f$ containing $-1$. Then $f : U \to U$ has degree $d$, and by \cite{BEF15} Theorem 1.10, $U$ is a bounded Jordan domain (in fact, a quasidisc).

Observe that $f^{-1}(0) = \{0\}$. Let $h$ be the lift of $f$ under $z = \exp(w)$ defined by

$$h(w) := 2w + p(\exp(w)) - p(-1) + \pi i.$$ 

Observe that $h((2k - 1)\pi i) = (4k - 1)\pi i$ for $k \in \mathbb{Z}$. Let $W_k$ be the connected component of $\exp^{-1}(U)$ containing $(2k - 1)\pi i$. By \cite{Ber95}, we have $\exp(J(h)) = J(f)$, so $W_k$ is a Fatou component of $h$, with $h(W_k) \subset W_{k+1}$. Since $U$ is a Jordan domain and is mapped to itself as a proper map of degree $d$, it follows that $W = W_0$ has the desired properties.

**Proof of Theorem 1.10.** Let $g$ be a finite Blaschke product of degree $d \geq 2$, and let $h$ and $W$ be as in Proposition 4.1. Let $\tilde{g}$ be the Blaschke product associated to $h : W \to f(W)$, say $\tilde{g} = \phi_1 \circ h \circ \phi_0^{-1}$ with Riemann maps $\phi_0 : W \to \mathbb{D}$ and $\phi_1 : f(W) \to \mathbb{D}$.

Restricted to $S^1$, both $g$ and $\tilde{g}$ are analytic covering maps of degree $d$, and therefore there is an analytic map $\theta : S^1 \to S^1$ such that

$$g \circ \theta = \tilde{g}. \tag{4.2}$$

In particular, $\theta$ is quasisymmetric, and can therefore be extended to a quasiconformal homeomorphism $\theta : \mathbb{D} \to \mathbb{D}$. Define a quasiregular map $\tilde{f} : \mathbb{C} \to \mathbb{C}$ by

$$\tilde{f}(z) := \begin{cases} h(z) & \text{if } z \notin W \\ \phi_1^{-1}(g(\theta(\phi_0(z)))) & \text{if } z \in W. \end{cases}$$

Since $\partial W$ and $\partial f(W)$ are Jordan curves, the maps $\phi_0$ and $\phi_1$ extend homeomorphically to the boundary. By \cite{BEF19}, $\tilde{f}$ is continuous at points of $\partial W$. By the Bers gluing lemma, it follows that $\tilde{f}$ is indeed quasiregular on $\mathbb{C}$.

Let $\mu$ be the dilatation of $\theta \circ \phi_0$, which is a Beltrami differential on $U$. Extend $\mu$ to $\mathbb{C}$ as follows: If $V$ is a component of the Fatou set of $h$ such that $h^n(V) = W$
for \( n > 0 \), let \( \mu|_V \) be the pull-back of \( \mu|_W \) under \( h^n \). On the complement of the backward orbit of \( W \), set \( \mu = 0 \). Then \( \mu \) is invariant under \( h \).

Apply the measurable Riemann mapping theorem to obtain a quasiconformal map \( \psi: \mathbb{C} \to \mathbb{C} \) whose dilatation is \( \mu \); then

\[
\tilde{f} := \psi \circ \tilde{f} \circ \psi^{-1}
\]

is an entire function. Moreover, consider \( U := \psi(W) \) and \( V := \psi(h(W)) = f(U) \). Then

\[
\Phi_0 := \theta \circ \phi_0 \circ \psi^{-1}: W \to \mathbb{D} \quad \text{and} \quad \Phi_1 := \phi_1 \circ \psi^{-1}: V \to \mathbb{D}
\]

are conformal isomorphisms and

\[
\Phi_1 \circ f = \phi_1 \circ \tilde{f} \circ \psi^{-1} = g \circ \theta \circ \phi_0 \circ \psi^{-1} = g \circ \Phi_0
\]
on \( W \). So \( g \) is an associated inner function of \( f: U \to V \).

The proof of Theorem 1.4 is similar. As with Proposition 4.1, we should first establish the existence of suitable subjects for our surgery.

**Proposition 4.2.** For every \( d \geq 2 \), there is an entire function \( \alpha_d \) having an invariant super-attracting Fatou component \( W \) which is a bounded Jordan domain, and such that \( f: W \to W \) is a proper map of degree \( d \).

Similarly, there is an entire function \( \rho_d \) having an invariant parabolic Fatou component \( W \) which is a bounded Jordan domain, and such that \( f: W \to W \) is a proper map of degree \( d \).

**Proof.** A function \( f \) with the properties required of \( \alpha_d \) was already described in (4.1), but since we do not require \( \alpha_d \) to restrict to a self-map of \( \mathbb{C} \setminus \{0\} \) here, we can also give simpler formulae, such as

\[
\alpha_d: \mathbb{C} \to \mathbb{C}; \quad z \mapsto \left( 1 - \cos \left( \frac{\pi \sqrt{z}}{2} \right) \right)^d.
\]

Then \( S(\alpha_d) = \{0, 1\} \), both 0 and 1 are super-attracting fixed points, and 0 is a degree \( d \) critical point of \( \alpha_d \).

Let \( W \) be the connected component of \( F(\alpha_d) \) containing 0. Then \( W \) is simply-connected, and \( \alpha_d: W \to W \) is a branched covering branched only over 0. Since both singular values of \( \alpha_d \) belong to (super-)attracting basins, the map \( \alpha_d \) is hyperbolic in the sense of [BFR15]. Again applying [BFR15] Theorem 1.10], \( U_0 \) is a quasidisc.

For \( \lambda > 0 \), define

\[
f_\lambda(z) := \frac{\alpha_d(z) + \lambda}{1 + \lambda}.
\]

Then 0 and 1 are still critical points of \( f_\lambda \), with critical values \( \lambda \) and 1. Moreover, \( f_\lambda \) is increasing on \([0, 1]\). It is easy to see that there is \( \lambda_0 > 0 \) such that the orbit of 0 converges to an attracting fixed point for \( \lambda < \lambda_0 \), to 1 for \( \lambda > \lambda_0 \), and to a parabolic fixed point for \( \lambda = \lambda_0 \). Set \( \rho_d := f_{\lambda_0} \), and let \( W \) be the Fatou component containing 0. Then \( \rho_d: W \to W \) is a degree \( d \) proper map. Moreover, since all singular values belong to attracting or parabolic basins, \( \rho_d \) is strongly geometrically
Finite in the sense of [ARS20]. By [ARS20] Theorem 1.8, W is again a bounded Jordan domain.

We now divide the connectivity locus $\mathcal{G}$ of finite Blaschke products from Theorem 1.4 into subclasses as follows. For $d \geq 2$, denote by $A_d$ the Blaschke products of degree $d$ having an attracting fixed point in $\mathbb{D}$, and by $P_d$ those having a triple fixed point on $S^1$. The elements of $A_d$ are called elliptic Blaschke products, while those of $P_d$ are said to be parabolic with zero hyperbolic step; see [Fle15]. Then $\mathcal{G} = \bigcup_k A_d \cup P_d$. Our goal is to extend the proof of Theorem 1.10 to the case of invariant attracting or parabolic components. To do so, we need to be able to replace the (non-dynamical) quasisymmetric map $\theta$ by a conjugacy between the two Blaschke products in question. This is possible by the following result. (See also [CvS18, Theorem A] for a much more general, and extremely deep result.)

Proposition 4.3. Let $d \geq 2$. Any two elements of $A_d$ are quasisymmetrically conjugate on $S^1$, and any two elements of $P_d$ are quasisymmetrically conjugate on $S^1$.

Proof. The maps in $A_d$ are hyperbolic in the sense of rational dynamics, and hence expanding on their Julia sets. The result is well-known in this case; see [dMvS93, Exercise 2.3 in Chapter II], and compare [Pet07] for a more general theorem. See also [BF14, Section 4.2].

For $P_d$, the result follows from [LLPS17, Proposition 2.3].

Proof of Theorem 1.4. Let $g \in \mathcal{G}$, say of degree $d \geq 2$. If $g \in A_d$, set $h := \alpha_d$ from Proposition 4.2, if $g \in P_d$, set $h := \rho_d$. Let $W$ be the corresponding invariant Fatou component, let $\phi: W \to \mathbb{D}$ be a Riemann map, and set $\tilde{g} := \phi \circ h \circ \phi^{-1}$.

Then by Proposition 4.3, there is a quasisymmetric homeomorphism $\theta: S^1 \to S^1$ such that $g \circ \theta = \theta \circ \tilde{g}$. Extend $\theta$ to a quasiconformal map $\theta: \mathbb{D} \to \mathbb{D}$ and define

$$
\tilde{f}: \mathbb{C} \to \mathbb{C}; \quad z \mapsto \begin{cases}
    h(z) & \text{if } z \notin W \\
    \phi^{-1}(g(\theta(\phi(z)))) & \text{if } z \in W.
\end{cases}
$$

The argument now proceeds exactly as in the proof of Theorem 1.10. The function $\tilde{f}$ is quasisymmetric. Straightening an invariant Beltrami differential that extends the complex dilatation of $\theta \circ \phi$, we obtain an entire function for which $g$ is a dynamically associated inner function. ■

Remarks. (a) To carry out the surgery, we could have started with any function $h$ having an invariant attracting or parabolic component $W$ of the required degree $d$. (For simplicity, our proof used the fact that $W$ is a Jordan domain, but it is easy to see that this is not essential.) In particular, let $\tilde{g}$ be the dynamically associated inner function, and let $g$ be a Blaschke product of the same degree and type (i.e., elliptic or parabolic with zero hyperbolic step) as $\tilde{g}$. If additionally $g$ and $\tilde{g}$ are quasiconformally equivalent, i.e. differ only by pre- and postcomposition with quasiconformal homeomorphisms of the disc, then there is an entire function $f$ quasiconformally equivalent to $h$ for which $g$ is a dynamically associated inner function. As mentioned in the introduction, it seems that a similar result holds for functions with...
finitely many singular values – or, more generally, Fatou components $W$ for which $W \cap S(f)$ is compact. We shall leave this question for discussion in a future paper.

(b) Observe that we could also have deduced Theorem 1.10 from (the proof of) Theorem 1.4, applying the surgery for attracting basins to the function $f$ defined in 4.1. From this, we obtain another self-map of $\mathbb{C} \setminus \{0\}$ realising a desired Blaschke product. Taking a lift of this second function, we obtain a wandering domain with the desired property.

(c) We have restricted to finite-valence attracting and parabolic Fatou components, where we obtained a complete description of the associated Blaschke products. However, let us briefly comment on the case of a finite-valence Baker domain, i.e. an invariant component of the Fatou set on which the iterates converge locally uniformly to infinity. Such a domain is called hyperbolic, simply parabolic or doubly parabolic, depending on whether the Denjoy-Wolff point of the associated Blaschke product is attracting, a double fixed point, or a triple fixed point. Compare [FH06]. Double-parabolic examples of every finite degree $d$ exist [FH06, Section 4]. The corresponding inner function belongs to $\mathcal{P}_d$, and we can apply our surgery to see that every element of $\mathcal{P}_d$ is realised as a dynamically associated inner function of an entire function with a Baker domain.

An analogue of Proposition 4.3 also holds for Blaschke products with $J(f) \neq S^1$ (again, this is a simple special case of [CvS18, Theorem A]). Therefore, starting with a function having a hyperbolic or simply-parabolic Baker domain of finite degree, we can apply the same surgery technique. However, as far as we are aware, the only known hyperbolic and simply-parabolic Baker domains of finite valence are univalent. Hence we cannot presently answer the question which finite Blaschke products arise as dynamically associated inner functions of entire functions with Baker domains.

5. INNER FUNCTIONS OF EXPONENTIAL MAPS

We begin with the following well-known observation concerning exponential maps $f_\lambda(z) = \lambda e^z$.

**Lemma 5.1 ([DG87, Lemma 1.1]).** $f_\lambda$ has a fixed point of multiplier $\mu \in \mathbb{C} \setminus \{0\}$ if and only if $\lambda = \mu \cdot e^{-\mu}$.

**Proof.** If $w$ is a fixed point $z$ of multiplier $\mu$, then $z = f_\lambda(z) = f'_\lambda(z) = \mu$. So $\mu = \lambda e^\mu$, as claimed. \[\square\]

The following shows that unisingular inner functions with an attracting fixed point are determined by their degree and their multiplier.

**Lemma 5.2.** Let $\mu \in \mathbb{D} \setminus \{0\}$, and let $2 \leq d \leq \infty$. Then, up to conjugacy by a Möbius automorphism of $\mathbb{D}$, there exists a unique inner function $g: \mathbb{D} \to \mathbb{D}$ of degree $d$ such that $g$ has an attracting fixed point of multiplier $\mu$ in $\mathbb{D}$, and such that $g$ has only one singular value in $\mathbb{D}$.
Proof. To prove existence, it is enough to exhibit the existence of a polynomial or entire function having an attracting fixed point of multiplier $\mu$, and having only one singular value. Indeed, then the dynamically associated inner function is of the stated form.

For $d < \infty$, such a function is given by the polynomial

$$z \mapsto \frac{\mu}{d} \cdot ((z + 1)^d - 1);$$

for $d = \infty$ the function $f_{\mu e^{-\nu}}$ has the desired properties by Lemma 5.1.

So it remains to prove uniqueness. Suppose that $g$ and $\hat{g}$ are both functions with the stated properties. Let $\hat{z}_0$ and $\tilde{z}_0$ be the corresponding fixed points, and $s$ and $\tilde{s}$ the singular values. By the Koenigs linearisation theorem, there is a simply-connected domain $U_0$ and a conformal isomorphism

$$\phi: U_0 \to B(0, |\mu|^{-1})$$

such that $\phi(g(z)) = \mu \phi(z)$ and $\phi(s) = 1$. An analogous function $\hat{\phi}$ on a domain $\hat{U}_0$ exists also for $\hat{g}$. Set

$$\psi_0 := \hat{\phi}^{-1} \circ \phi: U_0 \to \hat{U}_0.$$ 

Then $\psi_0$ conjugates $g$ to $\hat{g}$ on $U_0$, with $\psi_0(z_0) = \hat{z}_0$ and $\psi_0(s) = \hat{s}$.

Now set $U_1 := g^{-1}(U_0) \subset U_1$. Then $g: U_1 \to U_0$ is either a branched covering of degree $d$, branched only over $s$ (if $d < \infty$), or a universal covering (otherwise); see [BFR15, Proposition 2.8]. The same is true for $\hat{g}$. It follows that we can lift $\psi_0$ to a map $\psi_1: U_1 \to \hat{U}_1$ such that $\psi_0(g(z)) = \hat{g}(\psi_1(z))$ and $\psi_1(z_0) = \tilde{z}_0$. We have $\psi_1(z) = \psi_0(z)$ near $z_0$, and hence by the identity theorem on all of $U_0$. In particular, $\psi_1(s) = \hat{s}$, and we can continue inductively.

In this manner, we obtain a conformal conjugacy $\psi$ between $g$ and $\hat{g}$ on

$$\bigcup g^{-n}(U_0) = \mathbb{D}.$$ 

In other words, $g$ and $\hat{g}$ are M"{o}bius conjugate, as claimed. 

We now study the family of maps $g_{a,b}$ as in (1.4).

**Proposition 5.3.** No two different maps $g_{a,b}$ are conformally conjugate. Moreover, $g_{a,b}$ has an attracting fixed point in $\mathbb{H}$ if and only if $a > 1$ or $a \leq 1$ and $|b| > \arccos(\sqrt{a}) - \sqrt{a} \cdot \sqrt{1 - a}$.

**Proof.** If $g_{a,b}$ and $g_{\hat{a},\hat{b}}$ are conformally conjugate, then the conjugacy $\psi$ must preserve the set $g_{a,b}^{-1}((\infty)) = g_{\hat{a},\hat{b}}^{-1}((\infty))$, which consists of the odd multiples of $\pi/2$. So $\psi$ is a translation by an integer multiple of $\pi$. Since it must also map singular values to singular values, we have $\pi(a \hat{b} + b) = \hat{a} \hat{b} + \hat{b}$. So $a = \hat{a}$ and $b - \hat{b} \in \pi \mathbb{Z}$. As $b, \hat{b} \in (-\pi/2, \pi/2]$, we see that $b = \hat{b}$ as required.

Recall that, by the Denjoy-Wolff theorem, for every $a$ and $b$ there is a point $\zeta_0 \in \mathbb{H} \cup \{\infty\}$ such that $g_{a,b} \to \zeta_0$ locally uniformly on $\mathbb{H}$. We claim that $\zeta_0 \neq \infty$. Indeed, recall that $g_{a,b}$ is $\pi$-periodic, and that $g_{a,b}(z) \to b + ai \in \mathbb{H}$ as $\text{Im } z \to +\infty$. Hence, if $z_n := g_{a,b}^n(z_0) \to \infty$ for some $z_0 \in \mathbb{H}$, we must have $\text{Im } z_n \to 0$. On the other hand, within any horizontal strip of bounded height we have

$$|\tan'(z)| = \frac{1}{|\cos(z)|^2} \geq C \cdot |\tan(z)|^2$$
for some constant $C$. So, in particular, $|g_{a,b}'(z_n)| \to \infty$. It follows that

$$\text{Im } z_{n+1} = \text{dist}(z_{n+1}, \mathbb{R}) \geq \text{dist}(z_n, \mathbb{R}) = \text{Im } z_n$$

for sufficiently large $n$. Since $\text{Im } z_n \to 0$ and $\mathbb{R}$ is completely invariant, this is possible only if $z_0 \in \mathbb{R}$.

Hence $\infty$ cannot be the Denjoy-Wolff point of $g_{a,b}$. In particular, $g_{a,b}$ has an attracting fixed point in $\mathbb{H}$ if and only if it does not have an attracting or parabolic fixed point in $\mathbb{R}$.

Now, if $g_{a,b}$ has a fixed point of multiplier $\mu > 0$ at $\alpha \in \mathbb{R}$, then $\alpha$ is not an odd multiple of $\pi/2$, and

$$\alpha = g_{a,b}(\alpha) = \mu \cdot (\cos \alpha)^2 \cdot \tan \alpha + b = \mu \cdot \cos \alpha \cdot \sin \alpha + b,$$

so

$$b = b_\mu(\alpha) = \alpha - \mu \cdot \cos \alpha \cdot \sin \alpha.$$

Note that $a(\alpha)$ is a strictly decreasing function of $\alpha$ on $[0, \pi/2)$, and it is an easy exercise to see that, for $\mu \leq 1$, $b_\mu(\alpha)$ is a strictly increasing function of $\alpha$.

To prove the claim, let us restrict to the case $b \in [0, \pi/2]$, which we can do by symmetry. If $g_{a,b}$ has a parabolic fixed point $\alpha$ in $\mathbb{R}$, then $a \leq 1$ and $\alpha \in [0, \pi/2]$. Therefore

$$b = \alpha - \cos \alpha \cdot \sin \alpha = \arccos \sqrt{a - \sqrt{a \cdot 1 - a}} =: \theta(a).$$

Moreover, for fixed $\alpha$, $a_\mu(\alpha)$ is an increasing function of $\mu$, while $b_\mu(\alpha)$ is a decreasing function of $\mu$. It follows that $g_{a,b}$ has an attracting fixed point in $\mathbb{R}$ if and only if $a < 1$ and $b < \theta(a)$, as claimed.

Proof of Theorem 1.6. Let $f$ and $U$ be as in the theorem, and let $g: \mathbb{H} \to \mathbb{H}$ be an inner function dynamically associated to $f^m$ on $U$. Then $g$ has an attracting fixed point in $\mathbb{H}$, and a single singular value in $\mathbb{H}$, which we may assume to be placed at $i$. Then $g: \mathbb{H} \to \mathbb{H} \setminus \{i\}$ is a universal covering map. So is $\tan$, and the two maps agree up to pre-composition by a Möbius transformation of the half-plane. Applying a suitable Möbius conjugacy to $g$, we see that it can be chosen of the form $g_{a,b} \in \mathcal{G}$.

Proof of Theorem 1.5. The characterisation of $\mathcal{G}$ is in Proposition 5.3, and claim (1) holds by assumption. If $f \in \mathcal{F}$, then by Theorem 1.6 there is an inner function $g \in \mathcal{G}$ dynamically associated to $f$, and this function is unique by the first part of Proposition 5.3. Finally, let $g \in \mathcal{G}$ have an attracting fixed point of multiplier $\mu \in \mathbb{D} \setminus \{0\}$ in $\mathbb{D}$. There is a unique $\lambda \in \mathbb{C} \setminus \{0\}$ such that $f_\lambda$ has a fixed point of multiplier $\mu$, namely $\lambda = \mu \cdot e^{-\mu}$. As we have just proved, there is a dynamically associated inner function $g_{a,b} \in \mathcal{G}$, and by Lemma 5.2 and the first part of Proposition 5.3 we have $g = g_{a,b}$, as required.

For the parabolic case, we use the following version of Lemma 5.2.
Lemma 5.4. Up to conformal conjugacy, \( \tan: \mathbb{H} \to \mathbb{H} \) is the only inner function of infinite valence that has a unique singular value in \( \mathbb{H} \) and that has a fixed point of multiplicity 3 in \( \mathbb{R} \).

Proof. The proof is similar to Lemma 5.2. Given two functions \( g \) and \( \tilde{g} \) with the stated properties, we can use Fatou coordinates to construct petals \( \psi \) of multiplicity 3 of infinite valence that has a unique singular value in \( \mathbb{H} \) and that has a fixed point of multiplicity 3 in \( \mathbb{R} \).

We can again lift \( \psi \) to a map \( \psi_0 \) on \( g^{-1}(U_0) \), chosen such that \( \psi_0(g(s)) = \tilde{g}(s) \), and it follows as before that \( \psi_0 = \psi_1 \) on \( U_0 \). The proof now proceeds as before, and we conclude that \( g \) and \( \tilde{g} \) are Möbius conjugate.

Proof of Theorem 1.7. Suppose that \( f \) and \( U \) satisfy the hypotheses of the theorem. Let \( \phi: U \to \mathbb{H} \) be a conformal isomorphism, and let \( g := \phi \circ f^n \circ \phi^{-1} \) be the dynamically associated inner function, where \( n \) is the period of the parabolic Fatou component \( U \).

Recall that \( g \) is of infinite valence and has only one singular value \( \alpha \in \mathbb{H} \). Consequently \( g: \mathbb{H} \to \mathbb{H} \setminus \{\alpha\} \) is a universal covering map. Applying a suitable Möbius conjugacy, \( g \) can be taken of the form \( g = g_{a,b} \) for unique choices of \( a > 0 \) and \( b \in (-\pi/2, \pi/2] \).

Since \( f^p \) has no fixed point in \( U \), the inner function \( g \) has no fixed point in \( \mathbb{H} \), so its Denjoy-Wolff point zeta is a fixed point, a double fixed point (with a single attracting direction along \( \mathbb{R} \)) or a triple fixed point (with two repelling directions along the real axis). As mentioned previously, the final case holds if and only if \( g \) has zero hyperbolic step; i.e.,

\[
\text{dist}_{\mathbb{H}}(g^k(z), g^{k+1}(z)) \to 0
\]

as \( k \to \infty \), for all \( z \in \mathbb{H} \). Here \( \text{dist}_{\mathbb{H}} \) denotes hyperbolic distance.

It is well-known that

\[
\text{dist}_U(f^{kn}(z), f^{(k+1)n}(z)) \to 0
\]

for \( z \in U \). Indeed, the proof of the existence of Fatou coordinates, see [Mil06, Chapter 10], shows that all \( z \in U \) eventually enter a attracting petal \( P \subset U \) on which \( f^n \) is conformally conjugate to the map \( z \mapsto z + 1 \) on the upper half-plane. So \( f^{kn}(z) \in P \) for large enough \( k \), and

\[
\text{dist}_U(f^{kn}(z), f^{(k+1)n}(z)) \leq \text{dist}_P(f^{kn}(z), f^{(k+1)n}(z)) = O(1/k).
\]

Since \( g \) is conformally conjugate to \( f^n|_U \), we see that \( g \) does indeed have zero hyperbolic step, and hence a triple fixed point at \( \zeta_0 \). By Lemma 5.4, we have \( g = \tan \), as claimed.

Remark. In the specific case of the parabolic exponential map \( f(z) = e^{z-1} \), we could proceed more directly, using the inherent symmetry of the Julia set. Indeed, the parabolic basin \( U \) intersects the real axis in the interval \((-\infty, 1)\). This interval is a hyperbolic geodesic of \( U \) by symmetry, and contains the singular value 0. For the inner function \( h = h_{a,b}: \mathbb{H} \to \mathbb{H} \), it follows that the hyperbolic
geodesic connecting the Denjoy-Wolff point to $\infty$ contains the singular value. From this, we easily conclude that $b = 0$, so that $h = a \cdot \tan(z)$, with $a \leq 1$. We have 

$$\text{dist}_H(z, a \cdot \tan(z)) \asymp \text{dist}_H(z, a \cdot z) = \log \frac{1}{a}$$

as $z \to 0$ in $\mathbb{H}$. Hence we must have $a = 1$, as claimed.

We note that similar results to Theorems 1.6 and 1.7 hold when the cycle of $U$ contains only one singular value and $f^n : U \to U$ is proper of degree $d$. Indeed, in this case the associated inner function $g$ is a finite-degree unicritical Blaschke product having connected Julia set, and the connectedness locus of unicritical Blaschke products has been described in detail in [Fle15, CFY17]. When $d = 2$, an elliptic Blaschke product fixing zero with multiplier $\lambda$ is given by

$$z \mapsto z \cdot \frac{z + \lambda}{1 + \lambda z},$$

see [BF14, Section 4.2.1], and a Blaschke product with a parabolic fixed point is given by the function (1.3). Hence, if $U$ is a periodic Fatou component of period $p$ whose orbit contains just one singular value, which is a critical value of degree 2, then one of the above Blaschke products is dynamically associated to $f^p : U \to U$.

6. A generalisation of exponential maps

We now generalise our considerations for exponential maps as follows.

**Theorem 6.1.** Suppose that $f$ is an entire function and $U$ is an unbounded forward-invariant Fatou component, $U$, on which $f$ has infinite valence, but such that $f^{-1}(a) \cap U$ contains exactly $p$ points, counting multiplicity, for some $a \in U$ and $p \geq 0$. Assume also that $S(f) \cap U$ is compact, and that an inner function dynamically associated to $f|_U$ has a finite number $q \geq 1$ of singularities on $\partial \mathbb{D}$. Then $f$ has a dynamically associated inner function of the form

$$g : \mathbb{D} \to \mathbb{D}; \quad z \mapsto B(z) \exp \left( -\sum_{j=1}^{q} \left( c_j e^{i\theta_j} + z \right) - b_j e^{i\theta_j} - z \right),$$

for some finite Blaschke product $B$ of degree $p$, real numbers $\theta_1, \ldots, \theta_q$, and positive real numbers $c_1, \ldots, c_q$.

Before we prove the theorem, let us note a special case.

**Corollary 6.2.** Suppose that $P, Q$ are polynomials of degree $\deg P \geq 0$ and $\deg Q \geq 1$. Suppose also that $\lambda \in \mathbb{C} \setminus \{0\}$ is such that the function

$$f(z) := \lambda P(z)e^{Q(z)},$$

has an unbounded forward-invariant Fatou component, $U$, containing the origin, on which $f$ has infinite valence and such that $S(f) \cap U$ is compact. Then $f$ has a dynamically associated inner function of the form (6.1), with $q \leq \deg Q$ and $p \leq \deg P$.

**Remark.** If $\lambda$ is sufficiently small, then all the conditions of this corollary hold; see, for example, [Six18, Lemma 7.1].
**Proof of Corollary 6.2 using Theorem 6.1.** There are at most $\deg P$ preimages of 0 under $f$ in $U$ (counting multiplicity), and any associated inner function has at most $\deg Q$ singularities on $\partial \mathbb{D}$ by Corollary 1.3. Hence the hypotheses of Theorem 6.1 are satisfied.

**Proof of Theorem 6.1.** Let $g$ be an inner function dynamically associated to $f$. We shall assume that the Riemann map $\phi : \mathbb{D} \to U$ is chosen so that $\phi(0) = a$. By Theorem 2.1, set $g = B \cdot S$, where $B$ is a Blaschke product and $S$ is a singular inner function of the form (2.1).

Since $S$ is never zero, and $a$ has exactly $p$ preimages under $f$, counting multiplicity, it follows that $B$ must be a finite Blaschke product of degree $p$. Note that this implies that $B$ has no singularities in the boundary of the disc.

It is easy to see, for example, by [Gar07, Theorem 6.2], that the singularities of $g$ correspond exactly to the support of $\mu$. Since $g$ has only $q$ singularities, there exist real numbers $\theta_1, \ldots, \theta_q$ and positive real numbers $c_1, \ldots, c_q$ such that $\mu$ is equal to $q$ point masses, each of mass $c_j$, at the points $e^{i\theta_j}$. The result follows.

We now give three applications of this result. Our first example notes that, for the functions studied in Theorems 1.5 and 1.7, we recover the family of maps $g_{a,b}$ from (1.4), up to conformal conjugacy.

**Example 6.1.** Suppose that $f$ has a Fatou component $U$ of period $n$ such that $U$ contains only one singular value of $f$, and such that $f^n : U \to U$ is of infinite valence. Then this restriction is a universal covering over a single point $a \in U$, and therefore Theorem 6.1 applies with $p = 0$ and $q = 1$.

In particular, suppose that $f(z) = \lambda e^z$, for some $\lambda \neq 0$, such that $f$ has a forward-invariant attracting or parabolic Fatou component, $U$. Then $U$ must contain the origin, which is the only singular value of $f$, and Corollary 6.2 applies with $P \equiv 1$, $p = 0$, $Q \equiv \text{Id}$ and $q = 1$.

The only Blaschke product of order zero is the rotation. Hence there exist $\sigma \in (-\pi, \pi]$, $c > 0$, and $\theta \in (-\pi, \pi]$ such that

$$g(z) = e^{i\sigma} \exp \left( \frac{c}{z - e^{i\theta}} \right).$$

Conjugating $g$ with a rotation if necessary, we can assume that $\theta = \pi$, in which case

$$g(z) = \exp \left( i\sigma + \frac{c - 1}{z + 1} \right).$$

This is equivalent to (1.2) and (1.4), with $\mu = \sigma + ic$ and $(a, b) = (c, \sigma)/2$, respectively.

In particular, where $U$ is a parabolic basin, and in particular for $f(z) = e^{z-1}$, we have $c = 2$ and $\sigma = 0$ by Theorem 1.7. So here $g$ takes the form

$$g(w) = \exp \left( \frac{2(w - 1)}{w + 1} \right).$$

**Example 6.2.** Suppose we are in the family $f(z) = \lambda ze^z$, so that $P \equiv \text{Id}$, $p = 1$, $Q \equiv \text{Id}$ and $q = 1$. Suppose that $f$ has a forward-invariant Fatou component, $U$, of
infinite valence, that contains the origin. It is then easy to see that the hypotheses of Corollary 6.2 all hold.

The fact that $q = 1$ means, again, that after the right choice of $\arg \phi'(0)$ we can take, for some positive $c$,

$$S(z) = \exp \left( \frac{c \frac{z}{z+1}-1}{z+1} \right).$$

For $B$, the fact that $p = 1$ means that $B$ is a Blaschke product of degree one. However, we also know that $f(0) = 0$ and so $g(0) = 0$. Thus, for some $\sigma > 0$, we have

$$g(z) = e^{i\sigma} \exp \left( \frac{c \frac{z}{z+1}-1}{z+1} \right).$$

Example 6.3. Suppose we are in the family $f(z) = \lambda e^{z^q}$, for some $q \in \mathbb{N}$, so that $P \equiv 1$ and $Q(z) = z^q$. Suppose that the hypotheses of Corollary 6.2 all hold. Since $f$ omits the origin, we get that the Blaschke product is just a constant. We also get, by obvious symmetry considerations, that the $\theta_j$ in (6.1) can be taken to be the $q$-th roots of unity, and the $c_j$ are all the same. Set $\omega = e^{2\pi i/q}$. Then there exists $\sigma > 0$ and $c > 0$ such that

$$g(z) = e^{i\sigma} \exp \left( -c \sum_{j=1}^{n} \frac{\omega^j + z}{\omega^j - z} \right).$$

7. Proof of Theorem 1.8

Proof of Theorem 1.8. It is easy to see that if $\lambda \in (0,1)$, then both critical values $\pm \lambda$ are in the immediate basin of attraction $U$ of the attracting fixed point at 0. It follows easily that $U = F(f)$. (This was already observed by Fatou [Fat26].) In particular, (1.1) holds.

For simplicity write $f$ for $f_{\lambda}$. Choose the Riemann map $\phi : \mathbb{D} \to U$ so that $\phi(0) = 0$ and $\phi'(0) > 0$. Then $\phi$ maps points on the real line to the real line, because of the obvious symmetry of $U$. Let $g$ be the inner function $g := \phi^{-1} \circ f \circ \phi$, and let

$$g = B \cdot S,$$

where $B$ is a Blaschke product and $S$ is a singular inner function, as usual.

Clearly $0$ is a simple zero of $f$, and so of $g$, and so of $B$. Notice that $f$ is $2\pi$-periodic. Notice also that $f^2$ (the second iterate) is $\pi$-periodic. Hence $J(f)$ is $\pi$-periodic. The zeros of $f$ are the points $\pm \zeta_n$ where

$$\zeta_n = n \pi, \quad \text{for } n \in \mathbb{N}. $$

Hence the other zeros of $g$, and so of $B$, are all of the form $\pm a_n$, for some increasing sequence with $a_n \to 1$ as $n \to \infty$. Thus we can write $B$ as

$$B(z) = z \prod_{n \geq 1} \frac{a_n^2 - z^2}{1 - a_n^2 z^2}. $$

(7.1)

We claim that $S$ is, in fact, absent. To prove this claim, suppose otherwise. If $D \subset U$ is a Jordan domain containing $[-\lambda, \lambda]$, then $f^{-1}(U \setminus D)$ has exactly two components. Indeed, by the elementary mapping properties of sin, the set
$f^{-1}(\partial D)$ consists of two curves tending to $\pm \infty$, symmetrically with respect to the real axis. By Theorem 1.2, the map $g$ has two singularities on $\partial \mathbb{D}$. Since $\pm 1$ are singularities of $B$, this means that $S$ has at most two singularities, which would need to be positioned at $\pm 1$. Since $U$ is symmetric on reflection in the imaginary axis, and since $f$ is an odd function, our choice of $\phi$ implies that $g$ is also an odd function. Hence $S$ is generated by two equal masses, each at $\pm 1$. In particular, by a calculation from (2.1), there exists $c > 0$ such that

$$S(z) = \exp \left( \frac{z^2 + 1}{c z^2 - 1} \right).$$

It follows that as $x \to 1$, we have that $S(x) \to 0$, and so $g(x) \to 0$. This is impossible, as $f(x)$ does not have a limit as $x \to \infty$. This contradiction proves our claim, and we have $g = B$ with $B$ as in (7.1).

Next we seek to find a formula for the $a_n$. Because of the periodicity of $J(f)$ the hyperbolic distance in $U$ from $\zeta_n$ to $\zeta_{n+1}$ is constant, and in fact equal to the hyperbolic distance in $U$ from 0 to $\zeta_1$. Call this distance $d$. By symmetry, the real axis is a hyperbolic geodesic of $U$. It follows that $\text{dist}(0, \zeta_n) = n \cdot d$. Then the hyperbolic distance in $D$ from 0 to $a_n$ is also $n \cdot d$, and so

$$\log \frac{1 + a_n}{1 - a_n} = n \cdot d,$$

from which we calculate

$$a_n = \frac{e^{nd} - 1}{e^{nd} + 1} = \frac{\mu^n - 1}{\mu^n + 1},$$

where $\mu = e^d \in (1, \infty)$.

Clearly $d$, and hence $\mu$ depends on $\lambda$. Write $\mu = \mu(\lambda)$; it remains to show that $\mu: (0, 1) \to (1, \infty)$ is a homeomorphism. Since $\phi(0) = g(0) = f(0) = 0$,

$$\lambda = f'(0) = g'(0) = \prod_{n \geq 1} a_n^2 = \prod_{n \geq 1} \left( \frac{\mu^n - 1}{\mu^n + 1} \right)^2.$$

In particular, $\lambda$ is uniquely determined by $\mu$. The function $x \mapsto (x - 1)/(1 + x)$ is strictly increasing on $[1, \infty)$. So $\lambda$ is a strictly increasing continuous function of $\mu$. Moreover, it is easy to see that $\lambda \to 0$ as $\mu \to 1$, and $\lambda \to 1$ as $\mu \to \infty$. □

8. Fatou components with infinitely many critical values

Proof of Theorem 1.9. It is easy to show that $f_\lambda$ has a completely invariant Fatou component, $U_\lambda$, which contains a right half-plane. Hence (1) holds.

For simplicity write $f$ for $f_\lambda$ and $U$ for $U_\lambda$. Note that 0 $\in U$, and indeed (by a calculation) $\mathbb{R} \subset U$. Note also that $f(\overline{x}) = \overline{f(x)}$, and so $U$ is symmetric on reflection on the real line.

Let $\alpha > 0$, and choose the Riemann map $\phi: \mathbb{H} \to U$ so that $\phi(i\alpha) = 0$ and $\phi'(0) > 0$. (We will choose $\alpha$ later). Then $\phi^{-1}$ maps points on the real axis to the positive imaginary axis, because of the symmetry of $U$. Let $h := \phi^{-1} \circ f \circ \phi$ be an inner function of the upper half-plane.
Note that \( f(w + 2\pi i) = f(w) + 2\pi i \) for \( w \in \mathbb{C} \). This means that \( U \) is periodic under translation of \( 2\pi i \). We can deduce that there exists \( \kappa > 0 \) such that
\[
\phi^{-1}(w + 2\pi i) = \phi^{-1}(w) - \kappa, \quad \text{for } w \in \mathbb{C}.
\]
It then follows that \( h(z - \kappa) = h(z) - \kappa, \) for \( z \in \mathbb{H} \).

We claim that \( h \) has one singularity, and this is at infinity. (Observe that we cannot apply Theorem 1.2 as the singular values of \( f \) are not compactly contained in \( U \).) Suppose that \( \zeta \) is such that \( |\zeta| \) is small. It can be shown by a calculation that the preimages under \( f \) of \( \zeta \) that are of large modulus are close to the points \(-\log |y_n| + iy_n\), where
\[
y_n = \begin{cases} 
\frac{4n+1}{2}\pi, & \text{for } n \in \mathbb{N}, \\
\frac{4n+3}{2}\pi, & \text{for } -n \in \mathbb{N}.
\end{cases}
\]

These points can be connected to infinity by two curves in \( U \) (one containing the points of positive imaginary part, and the other containing the points of negative imaginary part) that are each homotopic to \((0, +\infty)\). This establishes the fact that \( h \) has only one singularity, since by transferring everything to the unit disc via a Möbius map we can deduce that \( g \) has exactly one singularity on \( \partial \mathbb{D} \), the point where all preimages of almost every \( z \in \mathbb{D} \) accumulate. Moreover, this singularity of \( h \) is at \( \lim_{x \to +\infty} \phi^{-1}(x) = i\infty \). This completes the proof of the claim.

Since \( h \) has no singularities in \( \mathbb{H} \), by Schwarz reflection extends to a transcendental meromorphic map of the whole plane, which we continue to call \( h \), and which maps \( \mathbb{H} \) to itself. For simplicity we now write
\[
h(z) := z + G(z) := z + \frac{G_1(z)}{G_2(z)},
\]
where \( G_1 \) and \( G_2 \) are entire. Then
\[
G(z + \kappa) = G(z),
\]
in other words, \( G \) is \( \kappa \)-periodic. Note that \( \kappa \) depends linearly on \( \alpha \); this can easily be seen by pre-composing \( \phi \) with a map \( z \mapsto cz \), for \( c > 0 \). Hence we can assume that \( \alpha \) is chosen so that \( \kappa = \pi \); in other words, \( G \) is \( \pi \)-periodic.

Next we locate the poles and fixed points of \( h \). The fixed points of \( h \) are the images under \( \phi^{-1} \) of the fixed points of \( f \). The fixed points of \( f \) are the points \( z_n := -\log \lambda + (2n + 1)\pi i \), for \( n \in \mathbb{Z} \). These points are accessible boundary points of \( U \), since, for each \( n \in \mathbb{N} \), the set \{ \( z_n + x : x > 0 \) \} lies in \( U \). Since the set of fixed points is \( 2\pi i \)-periodic, the fixed points of \( h \), which are equal to \( w_n := \phi^{-1}(z_n) \), are a \( \pi \)-periodic set of real numbers; this follows from our choice of \( \alpha \) above. Since the fixed points of \( f \) are all simple, these are all simple fixed points of \( h \).

Now we locate the poles of \( h \). Consider the line segments
\[
\gamma_n := \{2n\pi i + x : x < 0\} \subset U, \quad \text{for } n \in \mathbb{Z}.
\]
These all land on the boundary of \( U \) (in the Riemann sphere) and so their preimages under \( \phi \) land on the boundary of \( \mathbb{H} \); in other words, the real line. Let \( \xi_n \in \mathbb{R} \) be the landing point of \( \phi^{-1}(\gamma_n) \). Since \( f \) tends to infinity on \( \gamma_n \), it is clear that \( \xi_n \) is a pole of \( h \). Since the set \( \{\gamma_n\}_{n \in \mathbb{Z}} \) is \( 2\pi i \)-periodic, the set \( \{\xi_n\}_{n \in \mathbb{Z}} \) must be \( \pi \)-periodic; again, this follows from our choice of \( \alpha \). Moreover, \( \phi^{-1}(\gamma_0) \) lands to 0.
Thus $h$ has poles at the points $\pi n$, for $n \in \mathbb{Z}$. It is easy to see that these poles must be simple, as otherwise $h$ could not preserve the upper half-plane.

Note that $h$ cannot have any critical points on the real line. For, if $x \in \mathbb{R}$ and $h'(x) = 0$, then close to $x$ the map $h$ behaves like a power map and so cannot preserve the upper half-plane. It follows that there is a fixed point between every two poles. We can deduce that the points $\pi n$ are the only poles of $h$. Since the points $z_n$ mentioned earlier are symmetrically placed with respect to lines $\gamma_n$, the same must be true of the placement of the $w_n$ compared to the poles. Thus the $w_n$ are at the odd multiples of $\pi/2$.

Since the poles of $h$ are exactly the zeros of the sine function, it follows that there is an entire function $h_2$ such that
\[
G_2(z) = e^{h_2(z)} \sin z.
\]

Similarly, the fixed points of $h$ (which are all simple) are the zeros of $G_1$. Hence there is an entire function $h_1$ such that
\[
G_1(z) = e^{h_1(z)} \cos z.
\]

We have now concluded that there is an entire function $H$ such that
\[
h(z) = z + e^{H(z)} \cot z.
\]

Note that $G$, and hence $e^{H(z)}$, is $\pi$-periodic.

Now, if $x > 0$ is large, then $f(x + iy) \approx x + iy + \lambda$. We can deduce that if $y > 0$ is large, then $h(x + iy) = x + iy + i\mu(x, y)$, where $\mu(x, y)$ is small. It follows that $e^{H(z)}$ is bounded, and so must be constant. Since $f$ maps the real line to itself and maps large values of $x$ close to $x + \lambda$, $g$ maps the positive imaginary axis to itself and, when $y$ is large, maps $iy$ close to $iy + \mu$ for some positive $\mu$. Thus $e^{H(z)}$ is the constant $-\mu$, and we have obtained that
\[
h(z) = z - \mu \cot z.
\]

It remains to show that $\mu = \lambda$. We use an argument from the hyperbolic metric. For a hyperbolic domain $U$ we denote by $\rho_U(z)$ the hyperbolic density at a point $z \in U$, and $d_U(z, w)$ the hyperbolic distance between points $z, w \in U$.

Recall that $\rho_H(iy) = 1/y$, for $y > 0$. Recall also that $U$ contains a right half-plane, $H$ say. It then follows from [Min17, Theorem 1] that
\[
\lim_{y \to +\infty} \frac{\rho_U(y)}{\rho_H(y)} = \lim_{y \to +\infty} \frac{\rho_U(y)}{\rho_H(iy)} = 1.
\]

Since conformal maps preserve hyperbolic distance, we know that
\[
\log y - \log \alpha = d_U(i\alpha, iy) = d_U(0, \phi(iy)), \quad \text{for } y \geq 0.
\]

We can then deduce from (8.1) and (8.2) that
\[
\lim_{y \to +\infty} \frac{\phi(iy)}{y} = 1.
\]

Next we note that, using the definition of $h$, we have
\[
\lim_{y \to +\infty} y d_H(iy, h(iy)) = \lim_{y \to +\infty} y d_H(iy, i(y + \mu \coth y)) = \lim_{y \to +\infty} y \log(1 + \mu/y) = \mu.
\]
Also, using the definition of $f$, together with (8.1) and (8.3),

$$
\lim_{y \to +\infty} y d_U(\phi(iy), f(\phi(iy))) = \lim_{y \to +\infty} y d_U(\phi(iy), \phi(iy) + \lambda) = \lim_{y \to +\infty} y \log(1 + \lambda/y) = \lambda.
$$

Since $d_H(iy, h(iy)) = d_U(\phi(iy), f(\phi(iy)))$, it follows that $\mu = \lambda$, as required. ■

9. Proof of Theorem 1.11

We first give a simple result about uniform convergence of finite Blaschke products in the unit disc, which we use in the proof of Theorem 1.11.

**Proposition 9.1.** Suppose that $(B_n)_{n \in \mathbb{N}}$ is a sequence of finite Blaschke products of degree $d$, which converge locally uniformly on $\mathbb{D}$ to a finite Blaschke product, $B$, of degree $d$. Then the convergence is, in fact, uniform on $\mathbb{D}$.

**Proof.** In general we denote the open ball with centre $w \in \mathbb{C}$ and radius $r > 0$ by

$$
D(w, r) := \{z \in \mathbb{C} : |z - w| < r\}.
$$

Let $\rho \in (0, 1)$ be such that all the zeros of $B$ lie in the disc $D(0, \rho)$. Set

$$
t := \min\{|B(z)| : |z| = \rho\} > 0.
$$

It follows from local uniform convergence that for all sufficiently large values of $n$, we have

$$
|B(z) - B_n(z)| < t \leq |B(z)|, \text{ for } |z| = \rho.
$$

It then follows from Rouché’s theorem that, for all sufficiently large values of $n$, all the zeros of $B_n$ lie in $D(0, \rho)$. Hence there exists $r \in (0, 1)$ such that all the zeros of all the $B_n$ lie in $D(0, r)$.

By an easy calculation, we can deduce that there exists $r' > 1$ such that, with $D := D(0, r')$, each $B_n$ is analytic in $D$, and the family $(B_n)_{n \in \mathbb{N}}$ is uniformly bounded in $D$. It then follows by the Vitali-Porter theorem, see, for example, [Sch93], that the $B_n$ converge locally uniformly to $B$ in $D$. The result follows, as $\mathbb{D}$ is a compact subset of $D$. ■

Now we give the the proof of Theorem 1.11.

**Proof of Theorem 1.11.** Let $(B_n)_{n \in \mathbb{N}}$ be a sequence of finite Blaschke products that is dense in the space of finite Blaschke products (in the topology of uniform convergence). Such a sequence exists, for example, by choosing functions of the form (1.1) with $d$ finite and all the variables $\theta, \text{Re} a_1, \text{Re} a_2, \ldots, \text{Re} a_d$, and $\text{Im} a_1 \text{Im} a_2, \ldots, \text{Im} a_d$ rational.

For each $n \in \mathbb{N}$ let $T_n$ be the translation $T_n(z) := z + 4n$, and let $D_n$ be the disc $D_n := D(4n, 1)$. It follows by [BEF+19] Theorem 5.3 that there exists a transcendental entire function $f$ having an orbit of bounded, simply-connected, escaping, wandering domains $(U_n)_{n \in \mathbb{N}}$ such that the following all hold.

(A) $\Delta'_n := D(4n, r_n) \subset U_n \subset D(4n, R_n) := \Delta_n$, where $0 < r_n < 1 < R_n$ and $r_n, R_n \to 1$ as $n \to \infty$.

(B) $f_n := T_{n+1} \circ B_n \circ T_n^{-1}$ is analytic on $\overline{\Delta_n}$, and $|f(z) - f_n(z)| \to 0$ as $n \to \infty$ uniformly on $\overline{\Delta_n}$; by “uniformly” we mean that for each $\epsilon > 0$ there exists $N \in \mathbb{N}$ such that $|f(z) - f_n(z)| < \epsilon$, for $z \in \Delta_n$ and $n \geq N$.

(C) $f : U_n \to U_{n+1}$ has the same degree as $B_n$. 
This completes the definition of the function \( f \). It remains to show that the Fatou components of \( f \) have dynamically associated inner functions with the claimed properties. Suppose that \( n \in \mathbb{N} \). Let \( \phi_n : \mathbb{D} \to U_n \) be the Riemann map such that \( \phi_n(0) = 4n \) and \( \phi'_n(0) > 0 \). Then
\[
(9.1) \quad g_n = \phi^{-1}_{n+1} \circ f \circ \phi_n
\]
is an inner function dynamically associated to \( f|_{U_n} \).

We need to be able to approximate the Riemann maps in (9.1), and we claim that \( \phi_n \to T_n \) locally uniformly on \( \mathbb{D} \) as \( n \to \infty \). To prove this claim, we first consider translated copies of \( U_n \), defined by
\[
U'_n := T_n^{-1}(U_n), \quad \text{for } n \in \mathbb{N}.
\]
Note that, for each \( n \in \mathbb{N} \), we have that \( D(0, r_n) \subset U'_n \subset D(0, R_n) \). Suppose that \( w_0 \in \mathbb{D} \). Then there exists a neighbourhood of \( w_0 \) that is contained in \( U'_n \) for all sufficiently large \( n \in \mathbb{N} \). Also, suppose that \( w \in \partial \mathbb{D} \). Then it follows by [(A)] that there exists a sequence of points \( w_n \in \partial U'_n \) such that \( w_n \to w \) as \( n \to \infty \). Hence \( U'_n \to \mathbb{D} \) in the sense of kernel convergence; see [Pom92b, p.13]. Set
\[
\phi'_n := T_n^{-1} \circ \phi_n, \quad \text{for } n \in \mathbb{N}.
\]
It then follows from the Carathéodory kernel theorem ([Pom92b, Theorem 1.8]) that \( \phi'_n \to \text{Id} \) locally uniformly in the unit disc as \( n \to \infty \), where \( \text{Id}(z) := z \). The claim above follows.

Suppose that \( B \) is a given Blaschke product, and suppose that \( B \) has degree \( d \). Let \( (n_p)_{p \in \mathbb{N}} \) be a sequence of integers such that the subsequence \( (B_{n_p})_{p \in \mathbb{N}} \) converges uniformly to \( B \) on \( \mathbb{D} \) as \( p \to \infty \). We can assume that each \( B_{n_p} \) has degree \( d \).

Note that it follows by [(C)] that the degree of each \( g_{n_p} \) is equal to \( d \). Observe that the theorem requires that the sequence of functions \( (g_{n_p})_{p \in \mathbb{N}} \) converges uniformly on \( \mathbb{D} \) to the function \( B \) as \( p \to \infty \). We shall prove first that this sequence converges locally uniformly to \( B \). We will then use Proposition 9.1 to deduce that this convergence is in fact uniform.

To prove local uniform convergence, suppose that \( K \subset \mathbb{D} \) is a given compact set. Choose \( r \in (0, 1) \) sufficiently close to 1 that \( K \subset \Delta \) where \( \Delta := D(0, r) \). It follows by the claim above that
\[
(9.2) \quad \hat{\epsilon}_n(z) := \phi_n(z) - T_n(z), \quad \text{for } z \in \mathbb{D},
\]
is analytic in \( \mathbb{D} \), and such that \( \sup_{z \in \Delta} |\hat{\epsilon}_n(z)| \to 0 \) as \( n \to \infty \). Similarly
\[
(9.3) \quad \hat{\epsilon}_n(z) := \phi^{-1}_n(z) - T_n^{-1}(z), \quad \text{for } z \in U_n,
\]
is analytic in \( U_n \), and such that \( \sup_{z \in \phi_n(\Delta)} |\hat{\epsilon}_n(z)| \to 0 \) as \( n \to \infty \). Finally, it follows by [(B)] above that, for all sufficiently large \( n \in \mathbb{N} \), we have that
\[
(9.4) \quad \epsilon_n(z) := f(z) - f_n(z), \quad \text{for } z \in \Delta_n,
\]
is analytic in \( \Delta_n \), and such that \( \sup_{z \in \phi_n(\Delta)} |\epsilon_n(z)| \to 0 \) as \( n \to \infty \).
Note that, by (B), (9.2), and (9.4), if \( n \in \mathbb{N} \) is sufficiently large, then
\[
f(\phi_n(z)) = f_n(\phi_n(z)) + \epsilon_n(\phi_n(z))
\]
\[
= T_{n+1}(B_n(T_n^{-1}(T_n(z) + \hat{\epsilon}_n(z)))) + \epsilon_n(\phi_n(z))
\]
\[
= B_n(z + \hat{\epsilon}_n(z)) + 4(n + 1) + \epsilon_n(\phi_n(z)), \quad \text{for } z \in K.
\]
(9.5)

It then follows, by (9.1), (9.3), and (9.5), that, for \( z \in K \) and \( n \in \mathbb{N} \) sufficiently large,
\[
g_n(z) = \phi_{n+1}^{-1}(f(\phi_n(z)))
\]
\[
= T_{n+1}(B_n(z + \hat{\epsilon}_n(z))) + 4(n + 1) + \epsilon_n(\phi_n(z))
\]
\[
+ \hat{\epsilon}_{n+1}(B_n(z + \hat{\epsilon}_n(z))) + 4(n + 1) + \epsilon_n(\phi_n(z))
\]
\[
= B_n(z + \hat{\epsilon}_n(z)) + \epsilon_n(\phi_n(z)) + \hat{\epsilon}_{n+1}(B_n(z + \hat{\epsilon}_n(z))) + 4(n + 1) + \epsilon_n(\phi_n(z)),
\]
and so
\[
g_n(z) - B_n(z) = \delta_n(z), \quad \text{for } z \in K,
\]
where \( \delta_n \) is an analytic function such that \( \max_{z \in K} |\delta_n(z)| \to 0 \) as \( n \to \infty \).

Since the sequence \( (B_n)_{n \in \mathbb{N}} \) converges uniformly to \( B \) in \( \mathbb{D} \), as \( p \) tends to infinity, we have, therefore, established that the subsequence \( g_{n_p} \) converges locally uniformly to \( B \) in \( \mathbb{D} \), as \( p \) tends to infinity. Uniform convergence then follows by Proposition 9.1. This completes the proof of Theorem 1.11. For, if \( g_{n_p} \to B \) uniformly on \( \mathbb{D} \), then, given \( \epsilon > 0 \), we can set \( U = U_{n_p} \) and \( V = U_{n_p+1} \) for a sufficiently large value of \( p \). Note that \( U \) and \( V \) are then successive wandering domains in the orbit of \( f \).

\[\Box\]

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