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**THE INVERSE RIEMANN MAPPING THEOREM FOR  
RELATIVE CIRCLE DOMAINS**

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## THE INVERSE RIEMANN MAPPING THEOREM FOR RELATIVE CIRCLE DOMAINS

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A subdomain  $\Omega$  contained in a domain  $A$  in the Riemann sphere is called a *relative circle domain* in  $A$  if each component of  $A - \Omega$  is either a closed disk or a point. Let  $\Omega$  be a relative circle domain in the unit disk  $U$  in the complex plane  $\mathbb{C}$ ; and let  $A$  be a simply connected proper subdomain of  $\mathbb{C}$ . Then  $\Omega$  is conformally homeomorphic to a relative circle domain in  $A$ .

### 1. Introduction.

Let  $A$  be any domain in the Riemann sphere  $\hat{\mathbb{C}}$ . A domain  $\Omega$  contained in  $A$  is called a *relative circle domain* in  $A$  if each (connected) component of  $A - \Omega$  is either a closed disk or a point. When  $A = \hat{\mathbb{C}}$ , a relative circle domain in  $\hat{\mathbb{C}}$  is called a circle domain. In [HS2], we have proved that if  $A$  has at most countably many boundary components, then any relative circle domain in  $A$  is conformally homeomorphic to a circle domain. In the case that  $A$  is a simply connected proper subdomain of the plane, we have the following corollary.

**Riemann Mapping Theorem for Relative Circle Domains.** *Let  $A$  be a simply connected domain in the complex plane  $\mathbb{C}$  with  $A \neq \mathbb{C}$ . Let  $\Omega$  be a relative circle domain in  $A$ . Then there exist a relative circle domain  $\Omega^*$  in the unit disk  $U = \{z : |z| < 1\}$  and a conformal homeomorphism  $f : \Omega \rightarrow \Omega^*$  which extends to a locally quasiconformal homeomorphism  $\tilde{f} : A \rightarrow U$  whose complex dilatation vanishes a.e. in  $\partial\Omega \cap A$ .*

It also follows by [HS2, Lemma 5.3] that the domain  $\Omega^*$  and the map  $f$  in the above theorem are unique up to Möbius transformations. In this paper, we will prove the following inverse theorem.

**Theorem 1.1** (Inverse Riemann Mapping Theorem for Relative Circle Domains). *Let  $\Omega$  be a relative circle domain in the unit disk  $U$ ; and let  $A \subseteq \mathbb{C}$  be a simply connected domain with  $A \neq \mathbb{C}$ . Then for any  $z_0 \in \Omega$  and  $z_0^* \in A$ , there exist a relative circle domain  $\Omega^*$  in  $A$  and a conformal homeomorphism  $f : \Omega \rightarrow \Omega^*$  which extends to a locally quasiconformal homeomorphism  $\tilde{f} : U \rightarrow A$  whose complex dilatation vanishes a.e. in  $\partial\Omega \cap U$ , and such that*

$$(1.1) \quad f(z_0) = z_0^*, \quad f'(z_0) \in (0, +\infty).$$

We note that  $f$  is uniquely determined if  $\Omega^*$  is. It follows by the fixed point index lemma in [HS2, §4] that  $\Omega^*$  is unique if  $A$  is bounded and convex (or more generally, bounded and star-shaped around  $z_0^*$ ). However, in general we do not know if  $\Omega^*$  is unique. The line (1.1) can be replaced by other conditions as well. For more discussions on this, see [Sch].

Similar results also hold for circle packings. For example, we have the following theorem. Its proof is similar to that of Theorem 1.1 (see also [HS1, §10]).

**Theorem 1.2.** *Let  $P$  be a circle packing whose carrier is the unit disk  $U$ ; and let  $A \subseteq \mathbb{C}$  be a simply connected domain with  $A \neq \mathbb{C}$ . Then there is a circle packing  $P^*$  whose carrier is  $A$  and whose graph is combinatorially equivalent to that of  $P$ . Moreover, given a pair of tangent circles  $c_0$  and  $c_1$  in  $P$  and a point  $z_0^*$  in  $A$ , we can choose  $P^*$  such that  $c_0^*$  is centered at  $z_0^*$  and the point of tangency between  $c_0^*$  and  $c_1^*$  is to the right of  $z_0^*$  on the horizontal line through  $z_0^*$ , where  $c_0^*$  and  $c_1^*$  are the circles of  $P^*$  corresponding to  $c_0$  and  $c_1$  respectively.*

The interested reader may wish to look up the related paper by Carter and Rodin [CR].

The rest of the paper will be devoted to the proof of Theorem 1.1. First, the case when  $\Omega$  has only a finite number of boundary components follows by the results of Brandt [Br] or Harrington [Har] (see also [Sch]). For completeness' sake, we will give a simple proof modelled on the approach of [Sch]. Next we will deal with the case when  $\partial U$  is an isolated boundary component of  $\partial\Omega$ . Then we proceed by taking a sequence of proper subdomains of  $\Omega$  and use the earlier results to build conformal mappings from those proper subdomains to relative circle domains in  $A$ . The key point is to show that (some subsequence of) these conformal mappings converge to what we need. In our argument, we will have to use the convergence results and the Schwarz Pick lemma proved in [HS2].

## 2. The Case Where $\Omega$ is Finitely Connected.

For any conformal mapping  $f : \Omega \rightarrow \Omega^*$ , we will denote by  $f^B$  the bijection induced by  $f$  from the boundary components of  $\Omega$  to the boundary components of  $f(\Omega)$ .

The following theorem is fundamental.

**Brandt-Harrington Uniformization Theorem.** *Let  $\Omega \subset \mathbb{C}$  be a domain with finitely many boundary components,  $B^0, B^1, \dots, B^n$ , and suppose that none of these components is a single point. Let  $A \subsetneq \mathbb{C}$  be a simply connected*

domain, and let  $P^1, \dots, P^n$  be compact connected sets in  $\mathbb{C}$ , such that  $P^j$  contains more than a single point and  $\mathbb{C} - P^j$  is connected for each  $j = 1, \dots, n$ . Let  $z_0 \in \Omega$  and  $z_0^* \in A$  be arbitrary. Then there are disjoint sets  $Q^1, \dots, Q^n \subset A$  and a conformal homeomorphism

$$f : \Omega \rightarrow A - \cup_{j=1}^n Q^j,$$

such that

- (1)  $Q^j$  is homothetic to  $P^j$  for  $j = 1, \dots, n$ ;
- (2)  $f^B(B^j) = \partial Q^j$  for  $j = 1, \dots, n$ ,  $f^B(B^0) = \partial A$ ; and
- (3)  $f(z_0) = f(z_0^*)$ ,  $f'(z_0) \in (0, \infty)$ .

Recall that a homothety is a transformation of the form  $z \rightarrow az + b$  with  $a > 0$  and  $b \in \mathbb{C}$ . Two sets are *homothetic* if one is the image of the other under a homothety.

Brandt [Br] and Harrington [Har] have independently proved this theorem, using different methods. We will now present a simple proof, somewhat in the spirit of the one given in [Sch].

*Proof.* We shall use Koebe's circle uniformization theorem. It says that there is a unique conformal map  $g : \Omega \rightarrow U$  such that  $g(\Omega)$  is a circle domain,  $g(z_0) = 0$ ,  $g'(z_0) > 0$ , and  $g^B(B^0) = \partial U$ . (Alternatively, one can replace this with the similar theorem about uniformization with slit domains.)

Assume, without loss of generality, that  $z_0^* = 0$ . Let  $A_t \subset \mathbb{C}$ ,  $t \in [0, 1]$  be a continuous one parameter family of simply connected domains, such that  $A_0 = U$ ,  $A_1 = A$ , and  $0 \in A_t$ . (The  $A_t$  are open sets, so continuity here means that the complements  $\hat{\mathbb{C}} - A_t$  vary continuously in the Hausdorff metric on  $\hat{\mathbb{C}}$ .) Similarly, for  $j = 1, \dots, n$ , let  $P_t^j$ ,  $t \in [0, 1]$ , be a continuous one parameter family of compact sets in  $\mathbb{C}$ , such that each  $P_0^j$  is a disk, each  $P_t^j$ ,  $t \in [0, 1]$  is homeomorphic to a closed disk, and  $P_1^j = P^j$  for  $j = 1, \dots, n$ . To be explicit, for  $t \in (0, 1)$  one may take  $P_t^j$  to be the disk in  $\mathbb{C}$  with boundary  $t\phi_j^{-1}(\{|z| = t\})$ , where  $\phi_j : \hat{\mathbb{C}} - P^j \rightarrow U$  is a conformal homeomorphism satisfying  $\phi_j(\infty) = 0$ ; and similarly for  $A_t$ .

Set  $\mathbb{R}_+ = \{r \in \mathbb{R} : r > 0\}$ , and let  $X = \mathbb{R}_+^n \times \mathbb{C}^n$ . For  $(r, c) \in X$ ,  $j = 1, \dots, n$  and  $t \in [0, 1]$ , let  $P_t^j(r, c)$  denote the image of  $P_t^j$  under the homothety  $z \rightarrow r_j z + c_j$ . For every  $t \in [0, 1]$  let  $M_t$  denote the set of all  $(r, c) \in X$  such that  $P_t^j(r, c) \subset A_t - \{0\}$  for each  $j = 1, \dots, n$ , and  $P_t^j(r, c) \cap P_t^k(r, c) = \emptyset$  when  $j, k \in \{1, \dots, n\}$  are distinct. The set  $\widetilde{M} = \{(r, c, t) \in X \times [0, 1] : (r, c) \in M_t\}$  is a relatively open subset of  $\mathbb{R}^n \times \mathbb{C}^n \times [0, 1]$ .

Define a map  $H : \widetilde{M} \rightarrow M_0$ , as follows. Take some  $p = (c, r, t) \in \widetilde{M}$ . Then  $D_p = A_t - \cup_{j=1}^n P_t^j(r, c)$  is a domain in  $\mathbb{C}$  that contains 0 and has boundary components  $\partial A_t, \partial P_t^1(r, c), \dots, \partial P_t^n(r, c)$ . By Koebe's circle uniformization

theorem there is a unique conformal map  $h_p : D_p \rightarrow U$  such that  $h_p(D_p)$  is a circle domain,  $h_p(0) = 0$ ,  $h'_p(0) > 0$  and  $h_p^B(\partial A_t) = \partial U$ . Since each  $P_0^j$  is a disk and  $A_0 = U$ , there is a unique  $p' = (r', c', 0) \in M_0 \times \{0\}$  such that  $h_p(D_p) = D_{p'}$  and  $h_p^B(P_t^j(r, c)) = P_0^j(r', c')$ . Now set  $H(p) = (r', c')$ . The map  $H$  is continuous and proper. ('Proper' means that the inverse image of a compact set in  $M_0$  is compact.) It is left to the reader to check that this follows from the multiply connected version of Carathéodory's Kernel Convergence Theorem [Gol, V§5] (or the details may be found in [Sch]).

We want to prove that  $H(M_1 \times \{1\}) = M_0$ . Assume for the moment that  $H$  is  $C^\infty$ -smooth. Let  $V \subset M_0$  be any open subset of  $M_0$  with compact closure in  $M_0$ , and let  $\omega$  be a  $3n$  dimensional differential form on  $M_0$  with support contained in  $V$ , whose integral over  $M_0$  is nonzero. Since  $\omega$  is top dimensional on  $M_0$ ,  $d\omega = 0$ . Because  $H$  is proper and  $\omega$  has compact support, the pullback  $\delta H(\omega)$  of  $\omega$  has compact support in  $\widetilde{M}$ , and therefore we may apply Stokes' theorem, which gives

$$\int_{\widetilde{M}} d\delta H(\omega) = \int_{\partial\widetilde{M}} \delta H(\omega).$$

Here,  $\partial\widetilde{M}$  denotes not the boundary of  $\widetilde{M}$  as a subset of  $X \times [0, 1]$ , but the boundary of  $\widetilde{M}$  as a manifold with boundary. That is,  $\partial\widetilde{M} = (M_0 \times \{0\}) \cup (-M_1 \times \{1\})$ , where  $-M_1$  means  $M_1$  with the orientation reversed. But  $d\delta H(\omega) = \delta H(d\omega) = \delta H(0) = 0$ , and therefore

$$(2.1) \quad \int_{M_0 \times \{0\}} \delta H(\omega) = \int_{M_1 \times \{1\}} \delta H(\omega).$$

For  $t \in \{0, 1\}$ , let  $I_t : M_t \rightarrow \widetilde{M}$  denotes the map  $I_t(c, r) = (c, r, t)$ . Note that, by construction,  $H \circ I_0 : M_0 \rightarrow M_0$  is the identity, and  $\int_{M_0} \omega \neq 0$ . So  $\int_{M_0} \omega$  is equal to the left side of (2.1), and the right side of (2.1) is not zero. In particular,  $H(M_1 \times \{1\})$  intersects the support of  $\omega$ , which is contained in  $V$ . Because this is valid for any open  $V \subset M_0$  with compact closure, we deduce that  $H \circ I_1(M_1)$  is dense in  $M_0$ . Since  $H \circ I_1$  is proper and continuous, this implies that  $H \circ I_1$  is surjective, which is what we wanted.

We do not know if  $H$  is really smooth. To prove that  $H \circ I_1$  is surjective without this assumption it is enough to show that  $H$  may be uniformly approximated by smooth proper maps  $H^* : \widetilde{M} \rightarrow M_0$  such that  $H^* \circ I_0 : M_0 \rightarrow M_0$  is the identity. Since this is straightforward, the details are left to the reader.

Recall that  $g : \Omega \rightarrow U$  is the conformal map such that  $g(\Omega)$  is a circle domain,  $g(z_0) = 0$  and  $g'(z_0) > 0$ . There is a  $(c', r') \in M_0$  such that  $D_{p'} = g(\Omega)$ , where  $p' = (c', r', 0)$ , and  $g^B(B^j) = \partial P_0^j(c', r')$ . Because  $H \circ I_1$  is surjective, there is a  $(c, r) \in M_1$  such that  $H(c, r, 1) = (c', r')$ . Now the

map  $f = h_p^{-1} \circ g : \Omega \rightarrow D_p$  is the required map, where  $p = (c, r, 1)$ . The sets  $Q^j$  are given by  $Q^j = P_1^j(c, r)$ . □

**Corollary 2.1.** *Theorem 1.1 holds if  $\Omega$  has finitely many boundary components.*

*Proof.* There is no loss of generality in assuming that no boundary component of  $\Omega$  is a single point. In the Brandt-Harrington uniformization theorem take  $P^j = \bar{U}$  for each  $j = 1, \dots, n$ . It tells us that there is a conformal map  $f$  of  $\Omega$  onto some relative circle domain in  $A$  with  $f(z_0) = z_0^*$ ,  $f'(z_0) > 0$ , and  $f^B(\partial U) = \partial A$ . Because each circle component of  $\partial\Omega$ , except  $\partial U$ , is mapped to a circle,  $f$  is smooth near  $\partial\Omega - \partial U$ , and hence extends to a  $K$ -quasiconformal map  $\tilde{f} : U \rightarrow A$ . Since  $\partial\Omega$  has zero measure, the condition that the complex dilatation of  $\tilde{f}$  vanishes a.e. in  $\partial\Omega \cap U$  is trivial. □

### 3. The Case $\partial U$ is Isolated in $\partial\Omega$ .

In this section we prove:

**Lemma 3.1.** *Theorem 1.1 holds if  $\partial U$  is an isolated component of  $\partial\Omega$ .*

*Proof.* Let  $C_1 = \partial U, C_2, C_3, \dots$  be all the circles in  $\partial\Omega$ . For each  $k > 1$ , let  $\Omega_k$  be the domain bounded by  $C_1, C_2, \dots, C_k$ . We have  $\Omega \subseteq \Omega_{k+1} \subseteq \Omega_k$ . Then Corollary 2.1 tells us that Theorem 1.1 holds for each  $\Omega_k$ . Thus, there are some relative circle domains  $\Omega_k^*$  and conformal homeomorphisms  $f_k : \Omega_k \rightarrow \Omega_k^*$  such that  $f_k^B(\partial U) = \partial A$ , and  $f_k(z_0) = z_0^*$ ,  $f'_k(z_0) > 0$ .

As  $\partial U$  is isolated in  $\partial\Omega$ , there is some  $r > 0, r < 1$ , such that  $U - D(r) \subseteq \Omega$ ; where  $D(r)$  is the disk of radius  $r$  with center at 0. We may choose  $r$  such that  $z_0$  is contained in  $D(r)$ . It follows that all  $f_k$ 's are defined (and analytic) in the annulus  $U - D(r)$ ; and if we let  $s = (1+r)/2$  then the restrictions of  $f_k$  to  $D(s) - D(r)$  have uniformly quasiconformal extensions  $\tilde{f}_k : \hat{C} - D(r) \rightarrow \hat{C}$ . Let  $\tilde{\Omega}_k = \Omega_k \cup (\hat{C} - D(r))$ ; and let  $g_k : \tilde{\Omega}_k \rightarrow \hat{C}$  be the mapping which is equal to  $f_k$  in  $\Omega_k \cap D(s)$  and identical to  $\tilde{f}_k$  in  $\hat{C} - D(r)$ . Then the images of  $g_k(\tilde{\Omega}_k)$  are all circle domains; and all  $g_k$ 's are uniformly quasiconformal mappings of circle domains. Using the Schottky groups generated by the inversions in the circles of the circle domains, we may extend each  $g_k$ , as in [HS2, §2], to some uniformly quasiconformal homeomorphism  $\tilde{g}_k : \hat{C} \rightarrow \hat{C}$ .

Clearly,  $g_k(z_0) = f_k(z_0) = z_0^*$ ; and  $g'_k(z_0) = f'_k(z_0)$  are uniformly bounded from below by the Schwarz Pick Lemma of [HS1] (see also Lemma 4.2 below). Eventually, by replacing by subsequences, we may assume that the  $f_k$  are convergent in the interior of  $\Omega$  to some conformal map  $f : \Omega \rightarrow A$  and that  $\tilde{g}_k$  are uniformly convergent (in the spherical metric) in  $\hat{C}$  to some quasiconformal homeomorphism  $\tilde{g} : \hat{C} \rightarrow \hat{C}$ .

We claim that  $f(\Omega)$  is a relative circle domain in  $A$ . Let  $J$  be a component of  $A - f(\Omega)$ . As  $\partial D(s) \subseteq \Omega$  and  $f = \tilde{g}$  near  $\partial D(s)$ , we have either  $J \subseteq \tilde{g}(D(s))$  or  $J \subseteq \tilde{g}(\hat{C} - D(s))$ . In the former case,  $J$  is a component of  $\hat{C} - \tilde{g}(\Omega)$ , and hence is a closed disk or a point. As  $U - D(r) \subseteq \Omega$ , the latter case would imply that  $\bar{J} \cap \partial A \neq \emptyset$ , and is excluded by the following lemma.  $\square$

**Lemma 3.2.**  *$\partial A$  is an isolated boundary component of  $f(\Omega)$ .*

*Proof.* Consider the quasiconformal homeomorphisms  $h_k : U \rightarrow A$  defined by  $h_k = \tilde{g}_k$  in  $D(s)$  and  $h_k = f_k$  in  $U - D(r)$ . Then the  $h_k$  converge to some map  $h : U \rightarrow A$  with  $h = f$  in  $U - D(r)$ . Then the lemma follows by Carathéodory’s Kernel Convergence Theorem for quasiconformal maps [LV, pg. 76].  $\square$

So,  $f(\Omega)$  is a relative circle domain in  $A$ . Let  $h_k, h$  be the mappings constructed in the proof of Lemma 3.2, and set  $\tilde{f} = h : U \rightarrow A$ . As  $h_k|_\Omega = f_k|_\Omega$ , by taking the limit we deduce that  $h|_\Omega = f|_\Omega = f$ , i.e.,  $\tilde{f}|_\Omega = f$ . In order to complete the proof of Lemma 3.1, it only remains to show that the complex dilatation of  $\tilde{f}$  vanishes a.e. in  $\partial\Omega \cap U$ . Since  $\tilde{f} = \tilde{g}$  near  $\partial\Omega \cap U$ , it suffices to show that the complex dilatation of  $\tilde{g}$  vanishes a.e. in  $\partial\Omega \cap U$ . But this follows by [HS2, Lemma 3.2] restated below, since the complex dilatations of  $g_k$  vanish in  $\Omega_k$  and hence a.e. in  $\partial\Omega$ .  $\square$

**Lemma 3.3.** *Let  $A$  be a domain in  $\hat{C}$ . Let  $g_k : A \rightarrow \hat{C}$  be a sequence of uniformly quasiconformal mappings which converge to a quasiconformal mapping  $g_\infty : A \rightarrow \hat{C}$ . Let  $\lambda_k : A \rightarrow \mathbb{C}$  denote the complex dilatation of  $g_k$ . Suppose that  $\lim_{k \rightarrow \infty} \lambda_k(z)$  exists for a.e.  $z \in B$ ; where  $B \subseteq A$ . Then the complex dilatation of  $g_\infty$  equals  $\lim_{k \rightarrow \infty} \lambda_k(z)$  for a.e.  $z \in B$ .*

#### 4. Schwarz Pick Lemma and Corollaries.

This section will prepare us for the final step in the proof of Theorem 1.1. We first recall the Schwarz Pick Lemma of [HS2, §5].

**Lemma 4.1** (Schwarz Pick Lemma for Relative Circle Domains). *Let  $A$  and  $A^*$  be simply connected domains in  $\hat{C}$  such that  $A \supseteq U \supseteq A^*$ . Let  $\Omega$  and  $\Omega^*$  be relative circle domains in  $A$  and  $A^*$  respectively. Suppose that  $f : \Omega \rightarrow \Omega^*$  is a conformal homeomorphism, and that  $f^B(\partial A) = \partial A^*$ . If  $f$  extends to a locally quasiconformal homeomorphism  $g : A \rightarrow A^*$  whose complex dilatation vanishes a.e. on  $\partial\Omega \cap A$ , then for any  $p, q \in \Omega \cap U$ ,*

$$(4.1) \quad d_{hyp}(f(p), f(q)) \leq d_{hyp}(p, q);$$

where  $d_{hyp}$  denotes the Poincaré metric in the unit disk. Furthermore, if equality holds for one pair  $p \neq q$ , then  $A = A^* = U$  and  $f$  is the restriction of a hyperbolic isometry of  $U$ .

Let  $A$  be a simply connected proper subdomain in  $\mathbb{C}$ . Let  $\delta(z, \partial A)$  denote the euclidean distance between  $z$  and  $\partial A$ ; and let  $|dz|$  denote the euclidean metric of  $\mathbb{C}$ . Define a new metric  $ds_A$  in  $A$  by

$$(4.2) \quad ds_A(z) = \frac{2|dz|}{\delta(z, \partial A)}.$$

In what follows,  $A$  will implicitly be equipped with the metric  $ds_A$ ; and we will use  $d_A(\cdot, \cdot)$  to denote the distance in  $A$  between any pair of points. It is easy to see that the ball  $\{z \in A : d_A(z, p) \leq r\}$  is compact for any  $p \in A$  and  $r \in (0, \infty)$ .

Now, suppose we are given a relative circle domain  $\Omega$  in  $U$ , a relative circle domain  $\Omega^*$  in  $A$ , and a conformal homeomorphism  $f : \Omega \rightarrow \Omega^*$  which extends to a locally quasiconformal homeomorphism  $\tilde{f} : U \rightarrow A$  whose complex dilatation vanishes a.e. in  $\partial\Omega \cap U$ . Then:

**Lemma 4.2.** *Considering  $\Omega$  as a subset of  $U$  with the Poincaré metric, the map  $f : \Omega \rightarrow A$  is locally an expansion.*

*Proof.* Let  $p$  be any point in  $\Omega$ . We want to show that the differential  $df(p)$  has norm  $\geq 1$ . For convenience, let us assume that  $p = 0$  and  $f(0) = 0$ . Replacing  $f$  by  $g = f/\delta(0, \partial A)$ , we may assume that  $\delta(0, \partial A) = 1$ . We need, then, to show that  $|f'(0)| \geq 1$ . This follows immediately from Lemma 4.1 since  $U \subseteq A$ . □

**Lemma 4.3.** *There is a universal constant  $\eta > 0$  such that*

$$(4.3) \quad d_A(f(p), f(q)) \geq \min\{\eta, \eta d_{hyp}(p, q)\}$$

*for any pair of points  $p, q$  in  $\bar{\Omega} \cap U$ .*

*Proof.* It is enough to prove (4.3) for  $p, q \in \Omega$ . Again, we may assume  $p = f(p) = 0$  and  $\delta(0, \partial A) = 1$ . Suppose that  $d_A(f(p), f(q)) \leq \eta_1$  for some  $\eta_1 > 0$ , which we assume is very small, say  $\leq \log(5/4)$ . Then  $|f(q)| \leq 1/4$ , and hence  $f(q) \in U$ . As  $U \subseteq A$ , Lemma 4.1 tells us that  $d_{hyp}(0, f(q)) \geq d_{hyp}(0, q)$ . Hence  $|q| \leq |f(q)| \leq 1/4$ . As  $\delta(0, \partial A) = 1$ , this clearly implies that  $\eta_2 d_{hyp}(0, q) \leq d_A(0, f(q))$  for some  $\eta_2 > 0$ . Letting  $\eta = \min\{\eta_1, \eta_2\}$ , we obtain (4.3). □

### 5. Proof of Theorem 1.1 in the General Case.

We now complete the proof of Theorem 1.1 for arbitrary  $\Omega$ . Let  $U_k$  be a sequence of Jordan domains contained in  $U$  such that  $\partial U_k \subseteq \Omega$ ;  $U_k \subseteq U_{k+1}$ ; and  $\bigcup_k U_k = U$ . Let  $\Omega_k = \Omega \cap U_k$ . Then  $\Omega_k$  is a relative circle domain in  $U_k$  and  $\partial U_k$  is isolated in  $\partial \Omega_k$ . So we may apply the Riemann mapping theorem for relative circle domains and the special case of Theorem 1.1 proved in §3 to conclude that for each  $k$ , there exist a relative circle domain  $\Omega_k^*$  in  $A$  and a conformal homeomorphism  $f_k : \Omega_k \rightarrow \Omega_k^*$  which extends to some locally quasiconformal homeomorphism  $\tilde{f}_k : U_k \rightarrow A$  whose complex dilatation vanishes a.e. in  $\partial \Omega \cap U_k$ . Moreover, we may require  $f_k$  to satisfy

$$(5.1) \quad f_k(z_0) = z_0^*, \quad f'_k(z_0) > 0.$$

The extension of the sequence of maps  $f_k : \Omega_k \rightarrow A$  to  $\tilde{f}_k : U_k \rightarrow A$  can be done inductively: in step 1, extend  $f_k|_{U_1 \cap \Omega}$  to a sequence of maps defined on  $U_1$ ; then in step 2, extend  $f_k|_{U_2 \cap \Omega}$  to a sequence of maps defined on  $U_2$  while agreeing in  $U_1$  with the extensions constructed in the previous step; and so on. In this way, we can make sure that the maps  $\tilde{f}_k$  are locally uniformly quasiconformal, i.e., for any open subset  $W$  whose closure is contained in  $U$ , the restrictions  $\tilde{f}_k|_W$  are uniformly quasiconformal (see also [HS2] for a similar argument).

By the Schwarz Pick lemma (or Lemma 4.2), we see that the  $f'_k(z_0)$  are uniformly bounded from below. So, by taking a subsequence, we may assume that  $f_k$  converges in  $\Omega$  to some conformal mapping  $f : \Omega \rightarrow A$ , and  $\tilde{f}_k$  converge to some locally quasiconformal mapping  $\tilde{f} : U \rightarrow A$ . Since the complex dilatation of  $\tilde{f}_k$  vanishes a.e. in  $\partial \Omega \cap U_k$ , by Lemma 3.3, the complex dilatation of  $\tilde{f}$  vanishes a.e. in  $\partial \Omega \cap U$ . It remains to show that  $f(\Omega)$  is a relative circle domain in  $A$ .

First of all, if  $c$  is a component of  $\partial \Omega$  other than  $\partial U$ , then  $c \subseteq \partial \Omega_k \cap U_k$  for sufficiently big  $k$ . Then the locally uniform convergence of  $\tilde{f}_k$  to  $\tilde{f}$ , or the argument of [HS2, §3], show that  $\tilde{f}(c)$  is a circle or a point. That is,  $f^B(c) = \tilde{f}(c)$  is a circle or a point.

Finally, let us show that  $f^B(\partial U) = \partial A$ ; or equivalently, that  $\partial A$  is a boundary component of  $f(\Omega)$ . Here, we will use Lemma 4.3. By dropping some  $U_k$ 's, we may assume that  $U_k \subseteq U_{k+1}$ , and that the hyperbolic distance between  $\partial U_k$  and  $\partial U_{k+1}$  (as subsets in  $U$ ) is at least one. Let  $k$  be a fixed positive integer. Then for each  $j > k + 1$ , Lemmas 4.3 and 4.1 imply that  $d_A(f_j(\partial U_k), f_j(\partial U_{k+1})) \geq \eta$ . Letting  $j \rightarrow \infty$ , we obtain  $d_A(f(\partial U_k), f(\partial U_{k+1})) \geq \eta$ . As a consequence, for an arbitrary but fixed point  $z \in U_1 \cap \Omega$  and for any big number  $d > 0$ , the  $d$ -neighborhood of  $f(z)$  is contained in the Jordan domain bounded by  $f(\partial U_k)$  if  $k > d/\eta$ . This implies that  $f^B(\partial U) = \partial A$ . Theorem 1.1 is thus complete.  $\square$

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# PACIFIC JOURNAL OF MATHEMATICS

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Generalized fixed-point algebras of certain actions on crossed products BEATRIZ ABADIE	1
Partitions, vertex operator constructions and multi-component KP equations MAARTEN BERGVELT and A. P. E. TEN KROODE	23
Holomorphy tests based on Cauchy's integral formula CARMEN CASCANTE and DANIEL PASCUS	89
The Euler characteristic of a nonpositively curved, piecewise Euclidean manifold RUTH CHARNEY and MICHAEL WALTER DAVIS	117
The invariant connection of a $\frac{1}{2}$ -pinched Anosov diffeomorphism and rigidity RENATO FERES	139
The inverse Riemann mapping theorem for relative circle domains ZHENG-XU HE and ODED SCHRAMM	157
Multipliers and Bourgain algebras of $H^\infty + C$ on the polydisk KEI JI IZUCHI and YASOU MATSUGU	167
Irreducible bimodules associated with crossed product algebras. II TSUYOSHI KAJIWARA and SHIGERU YAMAGAMI	209
Elliptic fibrations on quartic $K3$ surfaces with large Picard numbers MASATO KUWATA	231
Automatic continuity for weakly decomposable operators RIDGLEY LANGE, SHENG-WANG WANG and YONG ZHONG	245
Crosscap number of a knot HITOSHI MURAKAMI and AKIRA YASUHARA	261
Symmetric minimal surfaces in $\mathbb{R}^3$ YOUYU XU	275



0030-8730(1995)171:1;1-H