

GREEN'S FUNCTION AND ANTI-HOLOMORPHIC DYNAMICS ON A TORUS

WALTER BERGWELER AND ALEXANDRE EREMENKO

ABSTRACT. We give a new, simple proof of the fact recently discovered by C.-S. Lin and C.-L. Wang that the Green function of a torus has either three or five critical points, depending on the modulus of the torus. The proof uses anti-holomorphic dynamics. As a byproduct we find a one-parametric family of anti-holomorphic dynamical systems for which the parameter space consists only of hyperbolic components and analytic curves separating them.

1. INTRODUCTION

Green's function on a torus T is defined as a solution of the equation

$$\Delta G = -\delta + \frac{1}{|T|},$$

normalized so that

$$\int_T G = 0.$$

Here δ is the delta-function, and $|T|$ is the area of T with respect to a flat metric.

We write the torus T as $T = \mathbb{C}/\Lambda$ with a lattice

$$\Lambda = \{m\omega_1 + n\omega_2 : m, n \in \mathbb{Z}\},$$

where $\tau = \omega_2/\omega_1$ satisfies $\text{Im } \tau > 0$. Recently C.-S. Lin and C.-L. Wang [24] discovered that Green's function has either three or five critical points, depending on τ . It is surprising that this simple fact was not known until 2010. In [9, 10] they study the corresponding partition of the τ -half-plane. Their proofs are long and indirect, using advanced non-linear PDE theory. Our paper is motivated by the desire to give a simple proof of their result that Green's function has either three or five critical points and to give a criterion for τ distinguishing which case occurs.

We have (see [24])

$$G(z) = -\frac{1}{2\pi} \log |\theta_1(z)| + \frac{(\text{Im } z)^2}{2 \text{Im } \tau} + C(\tau),$$

where θ_1 is the first theta-function. Here and in the following we use the notation of elliptic functions as given in [1, 18]. We note that the notation in [3, 32, 33] is different, see the remark following the theorem below.

Critical points of G are solutions of the equation

$$(1) \quad \zeta(z) + az + b\bar{z} = 0,$$

The second author is supported by NSF grant DMS-1361836.

where the constants a and b are uniquely defined by the condition that the left hand side is Λ -periodic. With $\zeta(z + \omega_j) = \zeta(z) + \eta_j$ for $j = 1, 2$ we thus have

$$\eta_1 + a\omega_1 + b\overline{\omega_1} = 0 \quad \text{and} \quad \eta_2 + a\omega_2 + b\overline{\omega_2} = 0.$$

With the Legendre relation $\eta_1\omega_2 - \eta_2\omega_1 = 2\pi i$ we obtain

$$(2) \quad b = -\frac{\pi}{|\omega_1|^2 \operatorname{Im} \tau} \quad \text{and} \quad a = -\frac{b\overline{\omega_1}}{\omega_1} - \frac{\eta_1}{\omega_1} = \frac{\pi}{\omega_1^2 \operatorname{Im} \tau} - \frac{\eta_1}{\omega_1}.$$

So the problem is to determine the number of solutions of (1) where a and b are given by (2).

Theorem. *The equation (1) has three solutions in T if $e_j\omega_1^2 + \eta_1\omega_1 = 0$ or*

$$(3) \quad \operatorname{Im} \left(\frac{2\pi i}{e_j\omega_1^2 + \eta_1\omega_1} - \tau \right) \geq 0$$

for some $j \in \{1, 2, 3\}$ and it has five solutions otherwise.

Here, as usual, $e_1 = \wp(\omega_1/2)$, $e_2 = \wp((\omega_1 + \omega_2)/2)$ and $e_3 = \wp(\omega_2/2)$. An elementary computation shows that the condition in the theorem is equivalent to

$$\min_{1 \leq j \leq 3} \left| \frac{e_j\omega_1^2 + \eta_1\omega_1}{\pi} \operatorname{Im} \tau - 1 \right| \leq 1$$

We note that $e_j\omega_1^2$ and $\eta_1\omega_1$ depend only on $\tau = \omega_2/\omega_1$. We may restrict to the case that $\omega_1 = 1$ so that $\tau = \omega_2$. Then (3) simplifies to

$$\operatorname{Im} \left(\frac{2\pi i}{e_j + \eta_1} - \tau \right) \geq 0.$$

As mentioned, a different notation for elliptic functions is used in [3, 32, 33]. There the periods are denoted by $2\omega_j$ and the definition of η_1 also differs by a factor 2. Thus in that terminology (3) takes the form

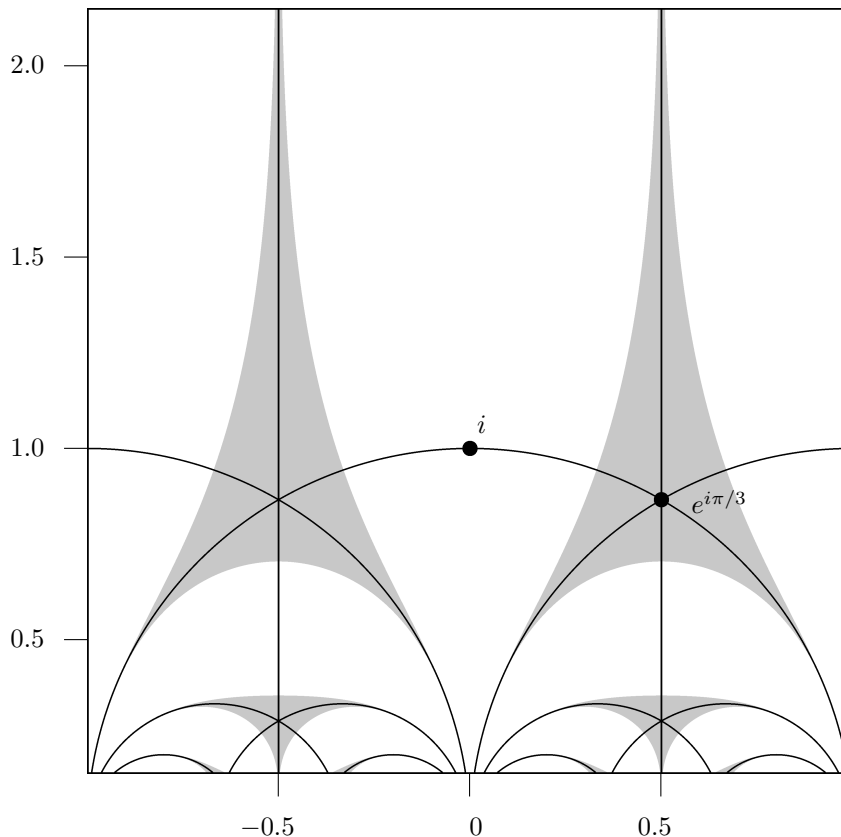
$$\operatorname{Im} \left(\frac{\pi i}{2(e_j\omega_1^2 + \eta_1\omega_1)} - \tau \right) \geq 0.$$

Figure 1 shows (in gray) the regions in the τ -plane where Green's function has 5 critical points; that is, the set of τ -values where (3) fails for all j . The range shown is $|\operatorname{Re} \tau| \leq 1$ and $0.15 \leq \operatorname{Im} \tau \leq 2.15$.

The standard fundamental domain consisting of those τ which satisfy the inequalities $\operatorname{Im} \tau > 0$, $-1/2 < \operatorname{Re} \tau \leq 1/2$ and $|\tau| \geq 1$, with $|\tau| = 1$ only if $\operatorname{Re} \tau \geq 0$, is in the upper middle of the picture. Its images under the modular group are also shown.

Our proof is based on Fatou's theorem from complex dynamics. Originally Fatou's theorem was proved to estimate from above the number of attracting cycles of a rational function. Then it was extended to more general classes of functions. The most surprising fact is that Fatou's theorem can be used sometimes to estimate the number of solutions of equations in settings where dynamics is not present. This was first noticed in [12]; the contents of this unpublished preprint is reproduced in [16, 8]. The paper [6] shows that Fatou's theorem can be used to prove under some circumstances the existence of critical points of a meromorphic function. In the papers [22, 20, 21, 19] Fatou's theorem was used to obtain upper estimates of the numbers of solutions of equations of the form

$$z = r(\overline{z}),$$

FIGURE 1. The regions given by (3) in the τ -plane.

with a meromorphic function r ; this permitted to prove a conjecture in astronomy [20, 21]. In the recent work [23], a topological classification of quadrature domains is obtained with a method based on Fatou's theorem.

As mentioned, Fatou [13, §30] stated his result originally only for rational functions. As pointed out for example in [5, Theorem 7], the proof extends to functions meromorphic in $\mathbb{C}$.

To state the version of Fatou's theorem that we need, we recall some definitions. Let S and T be Riemann surfaces and let $f: S \rightarrow T$ be holomorphic. A point $c \in S$ is called a *critical* if $f'(c) = 0$; this condition does not depend on the local coordinates.

We say that a curve $\gamma: [0, 1) \rightarrow S$ *escapes* if for every compact subset K in S there exists $t_0 \in (0, 1)$ such that $\gamma(t) \notin K$ for $t \in [t_0, 1)$. A curve $\gamma: [0, 1) \rightarrow S$ is called an *asymptotic curve* of f if γ escapes and the limit $\lim_{t \rightarrow 1} f(\gamma(t))$ exists and is contained in T . This limit is called an *asymptotic value* of f . The following result is due to Hurwitz [17].

Hurwitz's Theorem. *If a holomorphic map between two Riemann surfaces has no critical points and no asymptotic curves, then it is a covering.*

This result can be deduced from the fact that covering maps are characterized by the path-lifting property: for every curve $\gamma: [0, 1] \rightarrow T$ and every $z_0 \in f^{-1}(\gamma(0))$

there exists a unique curve $\gamma^*: [0, 1] \rightarrow S$ such that $\gamma = f \circ \gamma^*$; see, for example, [2, Theorem 9.1], where the term “complete covering” is also used. Note also that critical points and asymptotic curves correspond to singularities of the inverse function; see [28, §XI.1].

A Riemann surface S is called *hyperbolic* if its universal covering is the unit disk [2]. A hyperbolic Riemann surface is equipped with the hyperbolic metric. We denote by $\lambda_S(z)|dz|$ the length element of the hyperbolic metric in S . The invariant form of the Schwarz lemma (see, for example, [31, Proposition I.2.8 (a)], [27, Theorem 2.11] or [4, Theorem 10.5]) says that a holomorphic map $f: S \rightarrow T$ between hyperbolic Riemann surfaces S and T satisfies $\lambda_T(f(z))|f'(z)| \leq \lambda_S(z)$, with strict inequality for all z , unless f is a covering, in which case the equality holds for all z .

For a holomorphic map $f: S \rightarrow S$ a point $z_0 \in S$ is called *fixed* if $f(z_0) = z_0$, and for such a point $f'(z_0)$ is called the *multiplier*. It is easy to verify that the multiplier does not depend on the local coordinate. A fixed point is called *attracting*, *neutral* or *repelling* depending on whether the modulus of its multiplier is less than, equal to or greater than 1, respectively. A neutral fixed point is called *rational* if the multiplier is a root of unity.

Fatou’s Theorem. *Let S be a hyperbolic Riemann surface and let $f: S \rightarrow S$ be a holomorphic map with an attracting fixed point $z_0 \in S$. Then f has a critical point or an asymptotic curve in S . Moreover, $f^n \rightarrow z_0$ locally uniformly in S .*

Proof. If f has no critical points and no asymptotic curves, then f is a covering. The Schwarz lemma yields $\lambda_S(z_0) = \lambda_S(f(z_0))|f'(z_0)| = \lambda_S(z_0)|f'(z_0)|$ and thus $|f'(z_0)| = 1$, contradicting the assumption that $|f'(z_0)| < 1$. The second statement also follows from the Schwarz lemma. $\square$

In applications to holomorphic dynamics, S is the immediate attraction basin of an attracting fixed point z_0 ; that is, the component of the Fatou set which contains z_0 . It then follows that the immediate attracting basin contains a critical point or an asymptotic curve.

We note that Fatou also proved a corresponding result for fixed points of multiplier 1 (and, consequently, rationally neutral fixed points). This also generalizes to functions meromorphic in the plane, as well as to the present context, but we do not use this result.

2. PROOF OF THE THEOREM

To prove the theorem we rewrite (1) as a fixed point equation

$$(4) \quad z = -\frac{1}{b} \left(\overline{\zeta(z)} + \overline{az} \right) =: g(z),$$

so g is an *anti*-meromorphic function in the plane. As the left hand side of (1) is Λ -periodic, we conclude from (4) that

$$(5) \quad g(z + \omega) = g(z) + \omega, \quad \omega \in \Lambda.$$

The function g does not map the plane into itself because it has poles, so the equation (5) does not permit to define a map of the torus T into itself. To remedy this, we consider the set P_0 of poles of g . For $n \geq 1$ we define inductively $P_n = g^{-1}(P_{n-1})$. Then all iterates of g are defined on the set $\mathbb{C} \setminus P_\infty$, where $P_\infty = \bigcup_{n=0}^\infty P_n$. Let J be the closure of P_∞ . Then the iterates of g form a normal family

in $\mathbb{C} \setminus J$, and this set is completely invariant under g . Thus – with an obvious extension of these concepts from holomorphic functions to anti-holomorphic ones – we call J the *Julia set* and its complement $F = \mathbb{C} \setminus J$ the *Fatou set* of g . The Fatou set is thus the maximal open subset of the plane such that $g(F) \subset F$. Evidently, F is Λ -invariant, so the map $g: F \rightarrow F$ descends to a map which is defined on an open subset of the torus T and maps this open subset to itself.

Let $\pi: \mathbb{C} \rightarrow \mathbb{C}/\Lambda = T$ be the projection map, $\tilde{F} = \pi(F)$, and $\tilde{g}: \tilde{F} \rightarrow \tilde{F}$ the induced map which satisfies $\tilde{g} \circ \pi = \pi \circ g$. The Riemann surface $\tilde{F}$ is a subset of the torus, and it is hyperbolic because its complement is infinite.

We apply the terminology attracting, neutral and repelling also to fixed points z_0 of anti-holomorphic maps f , considering $\bar{\partial}f(z_0)$ as the multiplier. Notice that

$$(6) \quad \overline{\bar{\partial}g(z)} = -\frac{1}{b}(\zeta'(z) + a) = \frac{1}{b}(\wp(z) - a).$$

To obtain holomorphic dynamics instead of the anti-holomorphic one, we consider the second iterates $h = g^2$ and $\tilde{h} = \tilde{g}^2$. Then we have

$$(7) \quad \tilde{h} \circ \pi = \pi \circ h.$$

Images of fixed points of g and h in F under π are fixed points of $\tilde{g}$ and $\tilde{h}$, respectively. By the chain rule, we have

$$(8) \quad h' = ((\bar{\partial}g) \circ g) \cdot \bar{\partial}g = ((\bar{\partial}g) \circ g) \cdot \overline{\bar{\partial}g}.$$

For a fixed point z_0 of g we thus obtain $h'(z_0) = |\bar{\partial}g(z_0)|^2$. Even though we will not need this fact, we observe that the multiplier of h at a fixed point of g is always a non-negative real number.

In order to apply Fatou's theorem to $\tilde{h}: \tilde{F} \rightarrow \tilde{F}$, we have to consider the critical points and asymptotic curves of $\tilde{h}$.

Lemma 1. *The map $\tilde{h}: \tilde{F} \rightarrow \tilde{F}$ has no asymptotic curves.*

Proof. We prove this by contradiction. Let $\tilde{\gamma}$ be an asymptotic curve of $\tilde{h}$ in $\tilde{F}$. Let γ be some lifting of $\tilde{\gamma}$ in F ; that is $\pi \circ \gamma = \tilde{\gamma}$. As $\tilde{\gamma}$ escapes from $\tilde{F}$, the curve γ escapes from F . By assumption, we have $\tilde{h}(\tilde{\gamma}(t)) \rightarrow \tilde{p}$ as $t \rightarrow 1$, for some $\tilde{p} \in \tilde{F}$, so $\tilde{h}(\pi(\gamma(t))) \rightarrow \tilde{p}$ as $t \rightarrow 1$. In view of (7) this yields $\pi(h(\gamma(t))) \rightarrow \tilde{p}$ as $t \rightarrow 1$. Because π is a covering we conclude that

$$(9) \quad h(\gamma(t)) \rightarrow p \quad \text{for some } p \in F,$$

with $\pi(p) = \tilde{p}$. Thus γ is an asymptotic curve of h in F .

Suppose that γ has a limit point $q \in \mathbb{C}$ as $t \rightarrow 1$; that is, there exists a sequence (t_j) tending to 1 such that $\gamma(t_j) \rightarrow q$. Then $q \in \partial F \subset J$. If q is neither a pole of g nor a preimage of such a pole under g , then h is holomorphic at q , with $h(q) \in J$ by the complete invariance of the Julia set. On the other hand, we have $h(q) = \lim_{j \rightarrow \infty} h(\gamma(t_j)) = p \in F$, which is a contradiction. If q is the preimage of a pole of g , then q is a pole of h . Thus $h(q) = \infty$, contradicting again $h(q) = p$.

This shows that the finite limit points of γ are poles of g . As the poles form a discrete subset of $\mathbb{C}$ we actually see that if γ has a finite limit point q , then $\gamma(t) \rightarrow q$ as $t \rightarrow 1$ and thus $\sigma(t) := g(\gamma(t)) \rightarrow \infty$ as $t \rightarrow 1$. On the other hand, $g(\sigma(t)) = h(\gamma(t)) \rightarrow p$ as $t \rightarrow 1$. Let E be a Λ -invariant set consisting of disjoint disks around the poles of g . It follows from (5) that

$$g(z) \rightarrow \infty \quad \text{as } z \rightarrow \infty, \quad z \in \mathbb{C} \setminus E.$$

This is a contradiction to $\sigma(t) \rightarrow \infty$ and $g(\sigma(t)) \rightarrow p$ as $t \rightarrow 1$. We have thus shown that γ has no finite limit points, meaning that $\gamma(t) \rightarrow \infty$ as $t \rightarrow 1$.

In order to show that this is impossible we note again that the singularities of h are the poles of g and their preimages under g . Since these preimages accumulate only at the poles of g (and at ∞) there exists a Λ -invariant set $E' \subset \mathbb{C}$ consisting of disjoint disks which contains all singularities of h . Since h satisfies

$$h(z + \omega) = h(z) + \omega, \quad \omega \in \Lambda,$$

by (5), it follows that

$$h(z) \rightarrow \infty \quad \text{as } z \rightarrow \infty, \quad z \in \mathbb{C} \setminus E'.$$

As before this is incompatible with $\gamma(t) \rightarrow \infty$ and $h(\gamma(t)) \rightarrow p$ as $t \rightarrow 1$. This completes the proof of the lemma. $\square$

We consider the equivalence relation on $\tilde{F}$ defined by $z \sim z'$ if $\tilde{h}^n(z) = \tilde{h}^m(z')$ for some non-negative integers m and n . The equivalence classes are called the *grand orbits*. We note that if the sequence $(\tilde{h}^n(z))$ converges for some $z \in \tilde{F}$, then for all z' in the grand orbit of z the sequence $(\tilde{h}^n(z'))$ converges to the same limit. We call this the limit of the grand orbit.

Lemma 2. *The set of critical points of $\tilde{h}$ belongs to at most 4 grand orbits under $\tilde{h}$.*

Proof. By (6), the equation $\bar{\partial}g(z) = 0$ is equivalent to $\wp(z) = a$, and has two solutions modulo Λ which define points c and $-c$ on T . Here and in other similar places we denote by $-c$ the point which corresponds to c by the conformal involution of the torus. If any of the points c and $-c$ is in $\tilde{F}$, then it is a zero of $\tilde{h}'$. By (8) the other zeros of $\tilde{h}'$ are $\tilde{g}^{-1}(\pm c) = \pm \tilde{g}^{-1}(c)$. Even though this is an infinite set on T , the critical points of $\tilde{h}'$ are thus contained in at most 4 grand orbits represented by c , $-c$, $\tilde{g}(c)$ and $-\tilde{g}(c)$. $\square$

Lemma 3. *Let z_0 be a fixed point of $\tilde{g}$. If $\tilde{h}^n(z) \rightarrow z_0$ as $n \rightarrow \infty$ for some z , then $\tilde{h}^n(\tilde{g}(z)) \rightarrow z_0$.*

Proof. We have $\tilde{h}^n \circ \tilde{g} = \tilde{g} \circ \tilde{h}^n$ for all $n \in \mathbb{N}$. Since $\tilde{h}^n(z) \rightarrow z_0$ this yields $\tilde{h}^n(\tilde{g}(z)) = \tilde{g}(\tilde{h}^n(z)) \rightarrow \tilde{g}(z_0) = z_0$. $\square$

Applying Fatou's theorem to the map $\tilde{h}: \tilde{F} \rightarrow \tilde{F}$, we deduce that $\tilde{h}$ and thus $\tilde{g}$ has at most two attracting fixed points. If $\tilde{F}$ is disconnected, we apply Fatou's theorem separately to each component that contains an attracting fixed point. As the π -image of an attracting fixed point of g is an attracting fixed point of $\tilde{g}$ we obtain

Lemma 4. *The function g has at most two attracting fixed points, modulo Λ .*

The map $\phi: T \rightarrow \overline{\mathbb{C}}$, $z \mapsto z - g(z)$, is well defined by (5). Let $J_\phi = 1 - |\bar{\partial}g|^2$ be the Jacobian determinant of ϕ . Then $D^+ = \{z \in T: J_\phi(z) > 0\}$ is the set where ϕ preserves the orientation and $D^- = \{z \in T: J_\phi(z) < 0\}$ is the set where ϕ reverses the orientation. As ϕ has one pole, a point w of large modulus has one preimage on T and the map is reversing orientation at this preimage. We conclude that the degree of ϕ equals -1 ; see [26, §5] for the definition of the degree.

Suppose first that all zeros of ϕ are in $D^+ \cup D^-$. Equivalently, g has no neutral fixed points. Denote by N^+ and N^- the numbers of zeros of ϕ in D^+ and D^-

respectively. Then $N^+ - N^-$ equals the degree of ϕ so that $N^+ - N^- = -1$ and thus

$$(10) \quad N^- = N^+ + 1.$$

For the number $N = N^+ + N^-$ of fixed points of g in T we thus find that

$$(11) \quad N = 2N^+ + 1.$$

Since $J_\phi = 1 - |\bar{\partial}g|^2$, the zeros of ϕ in D^+ are attracting fixed points of g while the zeros of ϕ in D^- are repelling fixed points of g . Thus Lemma 4 yields that

$$(12) \quad N^+ \leq 2.$$

It follows from (11) and (12) that $N \leq 5$.

On the other hand, since ϕ is odd and Λ -periodic it easily follows that the half-periods $\omega_1/2$, $\omega_2/2$ and $\omega_3/2 = (\omega_1 + \omega_2)/2$ are zeros of ϕ . Equivalently, they are fixed points of g . Thus we have $N \geq 3$. Altogether, since N is odd by (11), it follows that $N = 3$ or $N = 5$.

It remains to determine the criterion distinguishing the cases. Suppose first that all three half-periods are in D^- ; that is, they are repelling fixed points of g . Then $N^- \geq 3$. This yields that $N^- = 3$ and $N^+ = 2$ so that $N = 5$ by (10) and (12). Suppose now that one half-period, say $\omega_j/2$, is not in D^- and thus in D^+ . Thus $\omega_j/2$ is an attracting fixed point of g and hence attracts a critical orbit by Fatou's theorem. However, since g is odd we see that $\omega_j/2$ in fact attracts both critical orbits. Thus, by Fatou's theorem, there are no other attracting fixed points. Thus $N^+ = 1$ and hence $N = 3$ in this case.

We see that $N = 3$ if and only if there exists $j \in \{1, 2, 3\}$ such that $\omega_j/2$ is an attracting fixed point of g ; that is, $|\bar{\partial}g(\omega_j/2)| < 1$. Using (6) this takes the form

$$(13) \quad \min_{1 \leq j \leq 3} \left| \frac{e_j}{b} - \frac{a}{b} \right| < 1.$$

Now (2) yields

$$\frac{a}{b} = -\frac{\bar{\omega}_1}{\omega_1} - \frac{\eta_1}{b\omega_1} = -\frac{\bar{\omega}_1}{\omega_1} + \frac{\eta_1|\omega_1|^2 \operatorname{Im} \tau}{\omega_1 \pi} = \frac{\bar{\omega}_1}{\omega_1} \left(-1 + \frac{\eta_1 \omega_1 \operatorname{Im} \tau}{\pi} \right)$$

and

$$\frac{e_j}{b} = -\frac{e_j|\omega_1|^2 \operatorname{Im} \tau}{\pi} = -\frac{\bar{\omega}_1}{\omega_1} \frac{e_j \omega_1^2 \operatorname{Im} \tau}{\pi}.$$

Substituting the last two equations in (13) yields

$$\left| \frac{e_j \omega_1^2 + \eta_1 \omega_1}{\pi} \operatorname{Im} \tau - 1 \right| < 1.$$

This is equivalent to strict inequality in (3). This completes the proof of the theorem in the case that all zeros of ϕ are in $D^+ \cup D^-$.

To deal with the case where this condition is not satisfied, we note that in the above arguments we may replace $\phi(z)$ by $\psi(z) = \phi(z) - w$ for any $w \in \mathbb{C}$. Noting that ϕ and ψ have the same Jacobian determinant we conclude that whenever all w -points of ϕ are in $D^+ \cup D^-$, then ϕ has either three or five w -points in T . Moreover, there are three w -points if and only if one of them is in D^+ .

We will use the following result [7, Proposition 3].

Lemma 5. *Let $D \subset \mathbb{C}$ be a domain and let $f: D \rightarrow \mathbb{C}$ be a harmonic map. Suppose that there exists $m \in \mathbb{N}$ such that every $w \in \mathbb{C}$ has at most m preimages. Then the set of points which have m preimages is open.*

Suppose now that ϕ has a zero in $T \setminus (D^+ \cup D^-)$. Then there are arbitrarily small w such that ϕ has a w -point in D^+ . Since for such w the function ϕ has three w -points, it follows from Lemma 5 that ϕ has three zeros in T . These zeros are the half-periods and we see that we have equality in (3). This completes the proof of the theorem.

Remark 1. The quantities $e_j \omega_1^2 + \eta_1 \omega_1$ occurring in (3) have the following representations via theta functions, see [32, p. 44]:

$$e_1 \omega_1^2 + \eta_1 \omega_1 = -\frac{\vartheta_2''(0)}{\vartheta_2(0)}, \quad e_2 \omega_1^2 + \eta_1 \omega_1 = -\frac{\vartheta_0''(0)}{\vartheta_0(0)}, \quad e_3 \omega_1^2 + \eta_1 \omega_1 = -\frac{\vartheta_3''(0)}{\vartheta_3(0)}.$$

The series for theta functions converge fast and provide a convenient way to compute Figure 1.

Let

$$F_j(\tau) = \frac{2\pi i}{e_j \omega_1^2 + \eta_1 \omega_1} - \tau$$

so that (3) takes the form $\text{Im } F_j(\tau) \geq 0$. It seems that F_j maps the components of the set of all τ in the upper half-plane where $\text{Im } F_j(\tau) > 0$ univalently onto the upper half-plane, but we have not been able to prove this.

Remark 2. Lin and Wang [24, Theorems 1.6 and 1.7] pay special attention to the case that $\tau = 1/2 + ib$, in which case Green's function has five critical points if and only if b is outside a certain interval $[b_0, b_1]$ where $b_0 \approx 0.35$ and $b_1 \approx 0.71$.

Here we note that the constants b_0 and b_1 are related to the so-called one-ninth constant Λ occurring in approximation theory; see [14, Section 4.5] for the definition and properties of this constant. As noted there, this constant was already computed by Halphen [15, p. 287] to six digits. It turns out that $\Lambda = e^{-2\pi b_0} = e^{-\pi/(2b_1)}$. The numerical values are $\Lambda = 0.10765391\dots$, $b_0 = 0.35472989\dots$ and $b_1 = 0.70476158\dots$.

To prove the above relation between these constants we note first that $e_1 \omega_1^2 + \eta_1 \omega_1 = 0$ if and only if $\vartheta_2''(0) = 0$ and thus if

$$\sum_{k=0}^{\infty} (2k+1)^2 h^{k(k+1)} = 0 \quad \text{where } h = e^{i\pi\tau}.$$

For $\tau = 1/2 + ib$ with $b \in \mathbb{R}$ we have $h = e^{i\pi/2 - \pi b}$ and hence

$$h^{k(k+1)} = \exp\left((i\pi - 2\pi b) \frac{k(k+1)}{2}\right) = (-x)^{k(k+1)/2} \quad \text{with } x = e^{-2\pi b}.$$

For $\tau = 1/2 + ib$ the condition that $e_1 \omega_1^2 + \eta_1 \omega_1 = 0$ is thus equivalent to

$$\sum_{k=0}^{\infty} (2k+1)^2 (-x)^{k(k+1)/2} = 0.$$

The smallest positive solution of the last equation is the one-ninth constant Λ ; see [14, Section 4.5]. Since $x = e^{-2\pi b}$ we deduce that $\Lambda = e^{-2\pi b_0}$.

The modular group leaves the sets where Green's function has five or three critical points invariant. The transformation $T(z) = (z-1)/(2z-1)$ satisfies $T(1/2 + ib) = 1/2 + i/(4b)$. This implies that $b_1 = 1/(4b_0)$ and $\Lambda = e^{-\pi/(2b_1)}$.

Remark 3. Figure 2 shows the Julia sets of the functions g corresponding to the square and the hexagonal lattice. The standard fundamental domains are marked

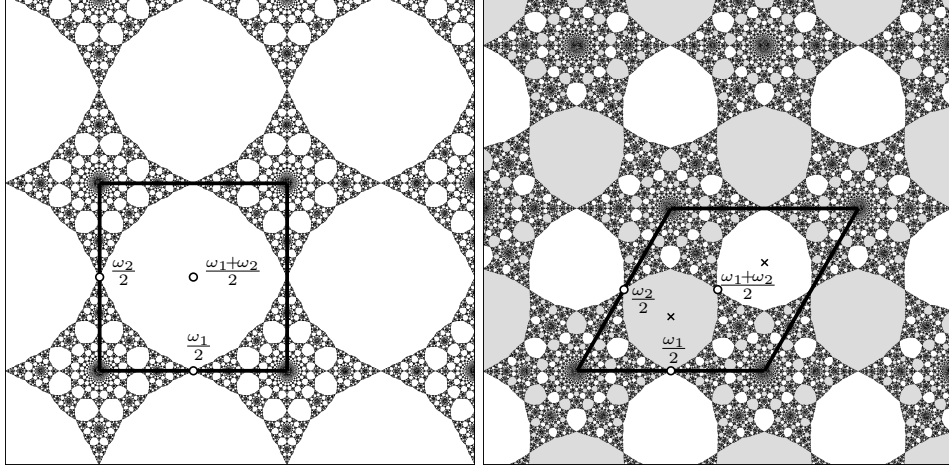


FIGURE 2. Julia sets corresponding to $\tau = i$ and $\tau = e^{i\pi/3}$.

by thick lines and the half-periods are marked by circles. For the square lattice, the half-periods are the only fixed points of g , with $(\omega_1 + \omega_2)/2$ attracting and the two other ones repelling. For the hexagonal lattice, all half-periods are repelling and there are the attracting fixed points $(\omega_1 + \omega_2)/3$ and $2(\omega_1 + \omega_2)/3$ marked by crosses.

Figure 3 shows the Julia set of the function corresponding to $\tau = 1/2 + ib_1$. The half-period $\omega_1/2$ is a parabolic fixed point with two petals. The two other half-periods are repelling fixed points.

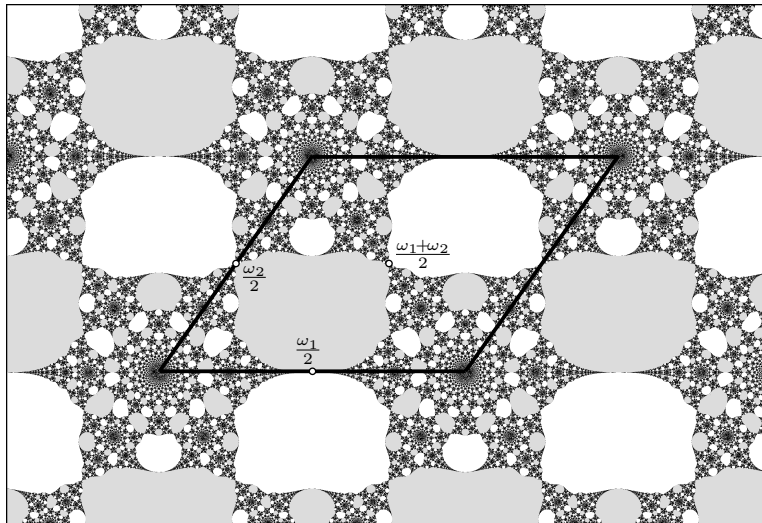
Comment. Besides the application in [22, 20, 21, 19], anti-holomorphic dynamics were studied for its own sake in [11, 30, 29] and elsewhere. In these papers, the iteration of the anti-holomorphic map $\bar{z}^2 + c$ was investigated. The bifurcation diagram in the c -plane for this map is called the Mandelbar set or Tricorn. It was noticed that the neutral cycle appears on a whole arc of the boundary of the hyperbolic component.

In the case we considered, a striking new phenomenon occurs: the neutral cycle occurs *everywhere* on the boundary of the hyperbolic component.

To be more precise, let H be the upper half-plane, so $\tau \in H$. Let X be the maximal open set of τ where G has three critical points, and $Y = H \setminus \bar{X}$. For τ in X , the critical orbits of $g = g_\tau$ tend to an attracting fixed point, while for $\tau \in Y$ they tend to two attracting fixed points. The open sets X and Y and their common boundary which is a piecewise analytic curve exhaust the whole parameter space! So a generic g_τ in our family has hyperbolic dynamics in a trivial way.

Such a situation occurs in holomorphic dynamics only in trivial cases [25, Theorem 2.2], and was not encountered so far in anti-holomorphic dynamics.

The point in a hyperbolic component at which the multiplier is zero is called the center of this hyperbolic component. Computation shows that the centers of X and Y in the standard fundamental domain are $\tau = i$ and $\tau = e^{2\pi i/3}$, corresponding to the square and hexagonal lattices respectively.

FIGURE 3. Julia set corresponding to $\tau = 1/2 + ib_1$.

We thank C.-S. Lin for his useful comments on this paper.

REFERENCES

- [1] L. V. Ahlfors, Complex analysis. An introduction to the theory of analytic functions of one complex variable. McGraw-Hill Book Company, Inc., New York-Toronto-London, 1953.
- [2] L. V. Ahlfors, Conformal invariants. Topics in Geometric Function theory, McGraw Hill, New York - Toronto - London, 1973.
- [3] N. I. Akhiezer, Elements of the theory of elliptic functions, Amer. Math. Soc., Providence, RI, 1990.
- [4] A. F. Beardon and D. Minda, The hyperbolic metric and geometric function theory, in “Quasiconformal Mappings and their Applications”, Narosa, New Delhi, 2007, pp. 9–56.
- [5] W. Bergweiler, Iteration of meromorphic functions. Bull. Amer. Math. Soc. 29 (1993), no. 2, 151–188.
- [6] W. Bergweiler and A. Eremenko, On the singularities of the inverse to a meromorphic function of finite order, Rev. Mat. Iberoamericana 11 (1995), no. 2, 355–373.
- [7] W. Bergweiler and A. Eremenko, On the number of solutions of a transcendental equation arising in the theory of gravitational lensing, Comput. Methods Funct. Theory 10 (2010), no. 1, 303–324.
- [8] W. Bergweiler, A. Eremenko and J. Langley, Zeros of differential polynomials in real meromorphic functions, Proc. Edinb. Math. Soc. 48 (2005), no. 2, 279–293.
- [9] C.-L. Chai, C.-S. Lin and C.-L. Wang, Mean field equations, hyperelliptic curves and modular forms: I, Camb. J. Math. 3 (2015), no. 1–2, 127–274.
- [10] C.-L. Chai, C.-S. Lin and C.-L. Wang, Mean field equations, hyperelliptic curves and modular forms: II, arXiv: 1502.03295.
- [11] W. D. Crowe, R. Hasson, P. J. Rippon and P. E. Strain-Clark, On the structure of the Mandelbar set, Nonlinearity 2 (1989), no. 4, 541–553.
- [12] A. Eremenko, Distribution of zeros of some real polynomials and iteration theory, preprint, Inst. for Low Temperature Physics and Engineering, Kharkov, 1989.
- [13] P. Fatou, Sur les équations fonctionnelles (deuxième mémoire), Bull. Soc. Math. France 48 (1920), 33–94.
- [14] S. R. Finch, Mathematical Constants, Cambridge University Press, Cambridge, 2003.
- [15] G. H. Halphen, Traité des fonctions elliptiques et de leurs applications, Gauthier-Villars, Paris, 1886.

- [16] A. Hinkkanen, Iteration and the zeros of the second derivative of a meromorphic function, Proc. London Math. Soc. 65 (1992), no. 3, 629–650.
- [17] A. Hurwitz, Sur les points critiques des fonctions inverses, C. R. Acad. Sci. Paris 144 (1907) 63–65.
- [18] A. Hurwitz, Vorlesungen über allgemeine Funktionentheorie und elliptische Funktionen, Springer-Verlag, Berlin – New York 1964.
- [19] D. Khavinson and E. Lundberg, Transcendental harmonic mappings and gravitational lensing by isothermal galaxies. Complex Anal. Oper. Theory 4 (2010), no. 3, 515–524.
- [20] D. Khavinson and G. Neumann, On the number of zeros of certain rational harmonic functions, Proc. Amer. Math. Soc. 134 (2006), no. 4, 1077–1085.
- [21] D. Khavinson and G. Neumann, From the fundamental theorem of algebra to astrophysics: a “harmonious” path, Notices Amer. Math. Soc. 55 (2008), no. 6, 666–675.
- [22] D. Khavinson and G. Świątek, On the number of zeros of certain harmonic polynomials, Proc. Amer. Math. Soc. 131 (2003), no. 2, 409–414.
- [23] S.-Y. Lee and N. G. Makarov, Topology of quadrature domains, J. Amer. Math. Soc., electronically published on May 11, 2015, DOI: <http://dx.doi.org/10.1090/jams828> (to appear in print).
- [24] C.-S. Lin and C.-L. Wang, Elliptic functions, Green functions and the mean field equations on tori, Ann. of Math. (2) 172 (2010), no. 2, 911–954.
- [25] C. McMullen, Families of rational maps and iterative root-finding algorithms, Ann. of Math. (2) 125 (1987), no. 3, 467–493.
- [26] J. W. Milnor, Topology from the differentiable viewpoint. Based on notes by David W. Weaver. Revised reprint of the 1965 original. Princeton University Press, Princeton, NJ, 1997.
- [27] J. W. Milnor, Dynamics in one complex variable, Princeton University Press, Princeton, NJ, 2006.
- [28] R. Nevanlinna, Eindeutige analytische Funktionen, Springer, Berlin - Göttingen - Heidelberg, 1953.
- [29] S. Mukherjee, S. Nakane and D. Schleicher, On multicorns and unicorns II: bifurcations in spaces of antiholomorphic polynomials, arXiv: 1404.5031.
- [30] S. Nakane and D. Schleicher, On multicorns and unicorns. I. Antiholomorphic dynamics, hyperbolic components and real cubic polynomials, Internat. J. Bifur. Chaos Appl. Sci. Engrg. 13 (2003), no. 10, 2825–2844.
- [31] W. P. Thurston, On the combinatorics and dynamics of iterated rational maps, edited by D. Schleicher and N. Selinger and with an appendix by Schleicher, in “Complex dynamics”, A K Peters, Wellesley, MA, 2009, pp. 3–137.
- [32] K. Weierstrass, Formeln und Lehrsätze zum Gebrauche der elliptischen Functionen, edited by H. A. Schwarz, Springer, Berlin, 1893.
- [33] E. T. Whittaker and G. N. Watson, A course of modern analysis, 4th edition, Cambridge University Press, Cambridge, 1927.

MATHEMATISCHES SEMINAR, CHRISTIAN-ALBRECHT-UNIVERSITÄT ZU KIEL LUDEWIG-MEYN-STRASSE 4, 24098 KIEL, GERMANY

E-mail address: `bergweiler@math.uni-kiel.de`

DEPARTMENT OF MATHEMATICS, PURDUE UNIVERSITY, WEST LAFAYETTE, IN 47907, USA

E-mail address: `eremenko@math.purdue.edu`