ON ALGEBRAIC DEPENDENCIES BETWEEN POINCARÉ FUNCTIONS

FEDOR PAKOVICH

ABSTRACT. Let $A$ be a rational function of one complex variable, and $z_0$ its repelling fixed point with the multiplier $\lambda$. Then a Poincaré function associated with $z_0$ is a function meromorphic on $\mathbb{C}$ such that $P_{A,z_0,\lambda}(0) = z_0$, $P'_{A,z_0,\lambda}(0) \neq 0$, and $P_{A,z_0,\lambda}(\lambda z) = A \circ P_{A,z_0,\lambda}(z)$. In this paper, we investigate the following problem: given Poincaré functions $P_{A_1,z_1,\lambda_1}$ and $P_{A_2,z_2,\lambda_2}$, find out if there is an algebraic relation $f(P_{A_1,z_1,\lambda_1},P_{A_2,z_2,\lambda_2}) = 0$ between them and, if such a relation exists, describe the corresponding algebraic curve $f(x,y) = 0$. We provide a solution, which can be viewed as a refinement of the classical theorem of Ritt about commuting rational functions. We also prove and extend previous results concerning algebraic dependencies between Böttcher functions.

1. INTRODUCTION

Let $A$ be a rational function of one complex variable of degree at least two, and $z_0$ its repelling fixed point with the multiplier $\lambda$. We recall that a Poincaré function $P_{A,z_0,\lambda}$ associated with $z_0$ is a function meromorphic on $\mathbb{C}$ such that $P_{A,z_0,\lambda}(0) = z_0$, $P'_{A,z_0,\lambda}(0) \neq 0$, and the diagram

$$
\begin{array}{cccc}
\mathbb{C} & \overset{\lambda z}{\longrightarrow} & \mathbb{C} \\
\downarrow_{P_{A,z_0,\lambda}} & & \downarrow_{P_{A,z_0,\lambda}} \\
\mathbb{CP}^1 & \overset{A}{\longrightarrow} & \mathbb{CP}^1
\end{array}
$$

commutes. The Poincaré function exists and is defined up to the transformation of argument $z \to cz$, where $c \in \mathbb{C}^*$ (see e.g. [12]). In particular, it is defined in a unique way if to assume that $P'_{A,z_0,\lambda}(0) = 1$. Such Poincaré functions are called normalized. In this paper, we will consider non-normalized Poincaré functions, so the explicit meaning of the notation $P_{A,z_0,\lambda}$ is following: $P_{A,z_0,\lambda}$ is some meromorphic function satisfying the above conditions. We say that a rational function $A$ is special if it is either a Lattès map, or it is conjugate to $z^{\pm n}$ or $\pm T_n$. The Poincaré functions associated with special functions can be described in terms of classical functions. Moreover, by the result of Ritt [29], these functions are the only Poincaré functions that are periodic.

In this paper, we investigate the following problem. Let $A_1$ and $A_2$ be non-special rational functions with repelling fixed points $z_1$, $z_2$, and $P_{A_1,z_1,\lambda_1}$, $P_{A_2,z_2,\lambda_2}$ corresponding Poincaré functions. Under what conditions there exists an algebraic curve $f(x,y) = 0$ such that

$$f(P_{A_1,z_1,\lambda_1},P_{A_2,z_2,\lambda_2}) = 0$$

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and, if such a curve exists, how it can be described? The simplest example of relation (1) is just the equality

\[ P_{A_1, z_0, \lambda_1} = P_{A_2, z_0, \lambda_2}, \]

which is known to have strong dynamical consequences. Specifically, equality (2) implies that \( A_1 \) and \( A_2 \) commute. On the other hand, by the theorem of Ritt (see [25] and also [26], [27]), every two non-special commuting rational functions of degree at least two have a common iterate. Thus, equality (2) implies that

\[ A_1^{\ell_1} = A_2^{\ell_2} \]

for some integers \( \ell_1, \ell_2 \geq 1 \). Moreover, the Ritt theorem essentially is equivalent to the statement that equality (2) implies equality (3), since it was observed already by Fatou and Julia ([8], [9]) that if two rational functions commute, then some of their iterates share a repelling fixed point and a corresponding Poincaré function.

To our best knowledge, the problem of describing algebraic dependencies between Poincaré functions has never been considered in the literature. Nevertheless, the problem of describing algebraic dependencies between Böttcher functions, similar in spirit, has been investigated in the papers [2], [14]. We recall that for a polynomial \( P \) of degree \( n \) a corresponding Böttcher function \( B_P \) is a Laurent series

\[ B_P = a_{-1} z + a_0 + \frac{a_1}{z} + \frac{a_2}{z^2} + \cdots \in z\mathbb{C}[[1/z]], \quad a_{-1} \neq 0, \]

that makes the diagram

\[ \mathbb{C} \xrightarrow{z^n} \mathbb{C} \]

\[ \mathcal{B}_{A_1} \downarrow \quad \mathcal{B}_{A_2} \]

\[ \mathbb{C} \mathbb{P}^1 \xrightarrow{A} \mathbb{C} \mathbb{P}^1 \]

commutative. In this notation, the result of Becker and Bergweiler [2] (see also [3]), states that if \( A_1 \) and \( A_2 \) are polynomials of the same degree \( d \), then the function \( \beta = B_{A_1} \circ B_{A_2}^{-1} \) is transcendental, unless either \( \beta \) is linear, or \( A_1 \) and \( A_2 \) are special (notice that since a polynomial cannot be a Lattès map, a polynomial is special if and only if it is conjugate to \( z^n \) or \( \pm T_n \)). Since the equality

\[ f(B_{A_1}(z), B_{A_2}(z)) = 0 \]

holds for some \( f(x, y) \in \mathbb{C}[x, y]\) if and only if the function \( \beta \) is algebraic, this result implies the absence of nontrivial algebraic dependencies of degree greater than one between \( B_{A_1}(z) \) and \( B_{A_2}(z) \) for non-special \( A_1 \) and \( A_2 \) of the same degree.

Subsequently, in the paper of Nguyen [14], was shown that the equality

\[ f(B_{A_1}(z^{d_1}), B_{A_2}(z^{d_2})) = 0 \]

holds for some integers \( d_1, d_2 \geq 1 \) if and only if there exist polynomials \( X_1, X_2, B \) and integers \( l_1, l_2 \geq 1 \) such that the diagram

\[ (\mathbb{C} \mathbb{P}^1)^2 \xrightarrow{(B, B)} (\mathbb{C} \mathbb{P}^1)^2 \]

\[ (X_1, X_2) \downarrow \quad (X_1, X_2) \]

\[ (\mathbb{C} \mathbb{P}^1)^2 \xrightarrow{(A_1^{l_1}, A_2^{l_2})} (\mathbb{C} \mathbb{P}^1)^2 \]
commutes. Notice that although the result of Nguyen treats the more general situation than the result of Becker and Bergweiler, the former does not formally imply the latter.

The main result of this paper is the following analogue of the result of Nguyen.

**Theorem 1.1.** Let $A_1, A_2$ be non-special rational functions of degree at least two, $z_1, z_2$ their repelling fixed points with multipliers $\lambda_1, \lambda_2,$ and $\mathcal{P}_{A_1,z_1,\lambda_1}, \mathcal{P}_{A_2,z_2,\lambda_2}$ Poincaré functions. Assume that $C : f(x, y) = 0$ is an irreducible algebraic curve, and $d_1, d_2$ are coprime positive integers such that the equality

$$f \left( \mathcal{P}_{A_1,z_1,\lambda_1}(z^{d_1}), \mathcal{P}_{A_2,z_2,\lambda_2}(z^{d_2}) \right) = 0$$

holds. Then $C$ has genus zero. Furthermore, if $C : f(x, y) = 0$ is an irreducible algebraic curve of genus zero with a generically one-to-one parametrization by rational functions $z \mapsto (X_1(z), X_2(z))$, and $d_1, d_2$ are coprime positive integers, then equality (7) holds for some Poincaré functions $\mathcal{P}_{A_1,z_1,\lambda_1}, \mathcal{P}_{A_2,z_2,\lambda_2}$ if and only if there exist positive integers $l_1, l_2, k$ and a rational function $B$ with a repelling fixed point $z_0$ such that the diagram

$$
\begin{array}{ccc}
(C\mathbb{P}^1)^2 & \xrightarrow{(B,B)} & (C\mathbb{P}^1)^2 \\
(X_1,X_2) \downarrow & & \downarrow (X_1,X_2) \\
(C\mathbb{P}^1)^2 & \xrightarrow{(A_1^{l_1},A_2^{l_2})} & (C\mathbb{P}^1)^2,
\end{array}
$$

commutes and the equalities

$$X_1(z_0) = z_1, \quad X_2(z_0) = z_2,$$

$$\text{ord}_{z_0} X_1 = d_1 k, \quad \text{ord}_{z_0} X_2 = d_2 k$$

hold.

Notice that Theorem 1.1 can be considered as a refinement of the Ritt theorem. Indeed, equality (2) is a particular case of condition (7), where

$$f(x, y) = x - y = 0$$

is parametrized by the functions $X_1 = z, X_2 = z$. Thus, in this case diagram (8) reduces to equality (3). More generally, considering the curve $x - R(y) = 0$, where $R$ is a rational function, we conclude that the equality

$$\mathcal{P}_{A_1,z_1,\lambda_1} = R \circ \mathcal{P}_{A_2,z_2,\lambda_2}$$

implies that there exist $l_1, l_2 \geq 1$ such that the diagram

$$
\begin{array}{ccc}
\mathbb{C}\mathbb{P}^1 & \xrightarrow{A_2^{l_2}} & \mathbb{C}\mathbb{P}^1 \\
& \downarrow R & \downarrow R \\
\mathbb{C}\mathbb{P}^1 & \xrightarrow{A_1^{l_1}} & \mathbb{C}\mathbb{P}^1
\end{array}
$$

commutes.

Notice also that Theorem 1.1 implies the following handy criterion for the algebraic independence of Poincaré functions.
Corollary 1.2. Let $A_1$ and $A_2$ be non-special rational functions of degrees $n_1 \geq 2$ and $n_2 \geq 2$, and $z_1, z_2$ their repelling fixed points with multipliers $\lambda_1, \lambda_2$. Then Poincaré functions $P_{A_1, z_1, \lambda_1}, P_{A_2, z_2, \lambda_2}$ are algebraically independent, unless there exist positive integers $l_1, l_2$ and $l'_1, l'_2$ such that $n_1^l_1 = n_2^{l_2}$ and $\lambda_1^{l'_1} = \lambda_2^{l'_2}$.

In addition to Theorem 1.1, we prove the following more precise version of the theorem of Nguyen, which formally includes and generalizes the result of Becker and Bergweiler.

Theorem 1.3. Let $A_1, A_2$ be non-special polynomials of degree at least two, and $B_{A_1}, P_{A_2}$ Böttcher functions. Assume that $C : f(x, y) = 0$ is an irreducible algebraic curve, and $d_1, d_2$ are coprime positive integers such that the equality
\[(11) \quad f(B_{A_1}(z^{d_1}), B_{A_2}(z^{d_2})) = 0\]
holds. Then $C$ has genus zero and can be parametrized by polynomials. Furthermore, if $C : f(x, y) = 0$ is an irreducible algebraic curve of genus zero with a generically one-to-one parametrization by polynomials $z \mapsto (X_1(z), X_2(z))$, and $d_1, d_2$ are coprime positive integers, then equality (11) holds for some Böttcher functions $B_{A_1}, P_{A_2}$ if and only if there exist positive integers $l_1, l_2$ and a polynomial $B$ such that the diagram
\begin{equation}
\begin{array}{cccc}
(CP^1)^2 & \xrightarrow{(B, B)} & (CP^1)^2 \\
(X_1, X_2) & \downarrow & (X_1, X_2) \\
(CP^1)^2 & \xrightarrow{(A_1^{d_1}, A_2^{d_2})} & (CP^1)^2,
\end{array}
\end{equation}
commutes, and the equalities
\[(13) \quad \deg X_1 = d_1, \quad \deg X_2 = d_2\]
hold. In particular, the equality
\[f(B_{A_1}(z), B_{A_2}(z)) = 0\]
implies that $C : f(x, y) = 0$ has degree one and some iterates of $A_1$ and $A_2$ are conjugate.

The approach of Nguyen to the study of algebraic dependencies relies on the fact that such dependencies give rise to invariant algebraic curves for endomorphisms $(A_1, A_2) : (CP^1)^2 \to (CP^1)^2$, given by the formula
\[(14) \quad (z_1, z_2) \mapsto (A_1(z_1), A_2(z_2)),\]
where $A_1$ and $A_2$ are polynomials (for example, for polynomials $A_1, A_2$ of the same degree $n$, after substituting $z^n$ for $z$ into (14) we obtain the equality
\[f(A_1 \circ B_{A_1}(z^{d_1}), A_2 \circ B_{A_2}(z^{d_2})) = 0,\]
implying that $f(x, y) = 0$ is $(A_1, A_2)$-invariant). Such invariant curves were completely classified by Medvedev and Scanlon in the paper [11], and the proof of the theorem of Nguyen relies crucially on this classification.

Our approach the the study of algebraic dependencies is similar. However, instead of the paper [11] we use the results of the recent paper [24] providing a classification of invariant curves for endomorphisms (14) defined by arbitrary non-special rational functions $A_1, A_2$. Notice that the paper [11] is based on the Ritt theory of polynomial decompositions (27), which does not extend to rational
functions. Accordingly, the approach of [24] is completely different and relies on the recent results [16, 18, 19, 20, 21] about semiconjugate rational functions, which appear naturally in a variety of different contexts (see e. g. [4, 7, 10, 11, 14, 17, 20, 22, 24]).

This paper is organized as follows. In the second section, we review the notion of a generalized Lattès map, introduced in [20], and some results about semiconjugate rational functions and invariant curves proved in [24]. In the third section, we prove Theorem 1.1. We also show that for rational functions that are not generalized Lattès maps equality (7) under the condition \( \gcd(d_1, d_2) = 1 \) implies the equality \( d_1 = d_2 = 1 \) (Theorem 3.6). Finally, in the fourth section, basing on results of the paper [17], which complements some of results of [11], we reconsider algebraic dependencies between Böttcher functions and prove Theorem 1.3.

2. Generalized Lattès maps and invariant curves

2.1. Generalized Lattès maps and semiconjugacies. Let us recall that a Riemann surface orbifold is a pair \( \mathcal{O} = (R, \nu) \) consisting of a Riemann surface \( R \) and a ramification function \( \nu : R \to \mathbb{N} \), which takes the value \( \nu(z) = 1 \) except at isolated points. For an orbifold \( \mathcal{O} = (R, \nu) \), the Euler characteristic of \( \mathcal{O} \) is the number

\[
\chi(\mathcal{O}) = \chi(R) + \sum_{z \in R} \left( \frac{1}{\nu(z)} - 1 \right).
\]

For orbifolds \( \mathcal{O}_1 = (R_1, \nu_1) \) and \( \mathcal{O}_2 = (R_2, \nu_2) \), we write \( \mathcal{O}_1 \leq \mathcal{O}_2 \) if \( R_1 = R_2 \) and for any \( z \in R_1 \) the condition \( \nu_1(z) | \nu_2(z) \) holds.

Let \( \mathcal{O}_1 = (R_1, \nu_1) \) and \( \mathcal{O}_2 = (R_2, \nu_2) \) be orbifolds, and let \( f : R_1 \to R_2 \) be a holomorphic branched covering map. We say that \( f : \mathcal{O}_1 \to \mathcal{O}_2 \) is a covering map between orbifolds if for any \( z \in R_1 \) the equality

\[
\nu_2(f(z)) = \nu_1(z) \deg_z f
\]

holds, where \( \deg_z f \) is the local degree of \( f \) at the point \( z \). If for any \( z \in R_1 \) the weaker condition

\[
\nu_2(f(z)) | \nu_1(z) \deg_z f
\]

is satisfied, we say that \( f : \mathcal{O}_1 \to \mathcal{O}_2 \) is a holomorphic map between orbifolds. If \( f : \mathcal{O}_1 \to \mathcal{O}_2 \) is a covering map between orbifolds with compact supports, then the Riemann-Hurwitz formula implies that

\[
\chi(\mathcal{O}_1) = d \chi(\mathcal{O}_2),
\]

where \( d = \deg f \). More generally, if \( f : \mathcal{O}_1 \to \mathcal{O}_2 \) is a holomorphic map, then

\[
\chi(\mathcal{O}_1) \leq \chi(\mathcal{O}_2) \deg f,
\]

and the equality is attained if and only if \( f : \mathcal{O}_1 \to \mathcal{O}_2 \) is a covering map between orbifolds (see [10], Proposition 3.2).

Let \( R_1, R_2 \) be Riemann surfaces and \( f : R_1 \to R_2 \) a holomorphic branched covering map. Assume that \( R_2 \) is provided with a ramification function \( \nu_2 \). In order to define a ramification function \( \nu_1 \) on \( R_1 \) so that \( f \) would be a holomorphic map between orbifolds \( \mathcal{O}_1 = (R_1, \nu_1) \) and \( \mathcal{O}_2 = (R_2, \nu_2) \) we must satisfy condition...
and it is easy to see that for any \( z \in R_1 \) a minimal possible value for \( \nu_1(z) \) is defined by the equality
\[
\nu_2(f(z)) = \nu_1(z) \text{GCD}(\deg_z f, \nu_2(f(z))).
\]
In case (18) is satisfied for any \( z \in R_1 \), we say that \( f \) is a minimal holomorphic map between orbifolds \( O_1 = (R_1, \nu_1) \) and \( O_2 = (R_2, \nu_2) \).

We recall that a Lattès map can be defined as a rational function \( A \) such that \( A : \mathcal{O} \to \mathcal{O} \) is a covering self-map for some orbifold \( \mathcal{O} \) on \( \mathbb{C}P^1 \) (see [13], [20]). Thus, \( A \) is a Lattès map if there exists an orbifold \( \mathcal{O} = (\mathbb{C}P^1, \nu) \) such that for any \( z \in \mathbb{C}P^1 \) the equality
\[
\nu(A(z)) = \nu(z) \deg_z A
\]
holds. By formula (16), such \( \mathcal{O} \) necessarily satisfies \( \chi(\mathcal{O}) = 0 \). Following [20], we say that a rational function \( A \) of degree at least two is a generalized Lattès map if there exists an orbifold \( \mathcal{O} = (\mathbb{C}P^1, \nu) \), distinct from the non-ramified sphere, such that \( A : \mathcal{O} \to \mathcal{O} \) is a minimal holomorphic self-map between orbifolds; that is, for any \( z \in \mathbb{C}P^1 \), the equality
\[
\nu(A(z)) = \nu(z) \text{GCD}(\deg_z A, \nu(A(z)))
\]
holds. By inequality (17), such \( \mathcal{O} \) satisfies \( \chi(\mathcal{O}) \geq 0 \). Notice that any special function is a generalized Lattès map and that some iterate \( A \circ l \), \( l \geq 1 \), of a rational function \( A \) is a generalized Lattès map if and only if \( A \) is a generalized Lattès map (see [24], Section 2.3).

Generalized Lattès map are closely related to the problem of describing semi-conjugate rational functions, that is, rational functions that make the diagram
\[
\begin{array}{ccc}
\mathbb{C}P^1 & \xrightarrow{B} & \mathbb{C}P^1 \\
X & \downarrow & X \\
\mathbb{C}P^1 & \xrightarrow{A} & \mathbb{C}P^1
\end{array}
\]
commutative. For a general theory we refer the reader to the papers [16], [18], [19], [20], [21]. Below we need only the following two results, which are simplified reformulations of Proposition 3.3 and Theorem 4.14 in [24].

The first result states that if the function \( A \) in (19) is not a generalized Lattès map, then (19) can be completed to a diagram of the very special form.

**Proposition 2.1.** If \( A, X, B \) is a solution of (19) and \( A \) is not a generalized Lattès map, then there exists a rational function \( Y \) such that the diagram
\[
\begin{array}{ccc}
\mathbb{C}P^1 & \xrightarrow{B} & \mathbb{C}P^1 \\
X & \downarrow & X \\
\mathbb{C}P^1 & \xrightarrow{A} & \mathbb{C}P^1 \\
Y & \downarrow & Y \\
\mathbb{C}P^1 & \xrightarrow{B} & \mathbb{C}P^1
\end{array}
\]
commutes, and the equalities
\[
Y \circ X = B^{od} \quad X \circ Y = A^{od},
\]
hold for some \( d \geq 0 \).
The second result states that every non-special rational function is semiconjugate to a rational function that is not a generalized Lattès map.

**Theorem 2.2.** Let $A$ be a non-special rational function of degree at least two. Then there exist rational functions $\theta$ and $F$ such that $F$ is not a generalized Lattès map and the diagram

$$
\begin{array}{ccc}
\mathbb{CP}^1 & \xrightarrow{F} & \mathbb{CP}^1 \\
\downarrow{\theta} & & \downarrow{\theta} \\
\mathbb{CP}^1 & \xrightarrow{A} & \mathbb{CP}^1.
\end{array}
$$

commutes. \hfill \square

### 2.2. Invariant curves.

Let $A_1, A_2$ be rational functions. We denote by

$$(A_1, A_2) : (\mathbb{CP}^1)^2 \rightarrow (\mathbb{CP}^1)^2$$

the map given by the formula

$$(z_1, z_2) \rightarrow (A(z_1), A(z_2)).$$

We say that an irreducible algebraic curve $C$ in $(\mathbb{CP}^1)^2$ is $(A_1, A_2)$-invariant if $(A_1, A_2)(C) = C$.

The simplest $(A_1, A_2)$-invariant curves are vertical lines $x = a$, where $a$ is a fixed point of $A_1$, and horizontal lines $y = b$, where $b$ is a fixed point of $A_2$. Other invariant curves are described as follows (see [24], Theorem 4.1).

**Theorem 2.3.** Let $A_1, A_2$ be rational functions of degree at least two, and $C$ an irreducible $(A_1, A_2)$-invariant curve that is not a vertical or horizontal line. Then the desingularization $\tilde{C}$ of $C$ has genus zero or one, and there exist non-constant holomorphic maps $X_1, X_2 : \tilde{C} \rightarrow \mathbb{CP}^1$ and $B : \tilde{C} \rightarrow \tilde{C}$ such that the diagram

$$
\begin{array}{ccc}
(\tilde{C})^2 & \xrightarrow{(B, B)} & (\tilde{C})^2 \\
\downarrow{(X_1, X_2)} & & \downarrow{(X_1, X_2)} \\
(\mathbb{CP}^1)^2 & \xrightarrow{(A_1, A_2)} & (\mathbb{CP}^1)^2
\end{array}
$$

commutes and the map $t \rightarrow (X_1(t), X_2(t))$ is a generically one-to-one parametrization of $C$. Finally, unless both $A_1, A_2$ are Lattès maps, $\tilde{C}$ has genus zero. \hfill \square

For a general description of $(A_1, A_2)$-invariant curves we refer the reader to the paper [24]. Below we need only the following description of invariant curves in case $A_1 = A_2$ (see [24], Theorem 1.2).

**Theorem 2.4.** Let $A$ be a rational function of degree at least two that is not a generalized Lattès map, and $C$ an irreducible $(A, A)$-invariant curve that is not a vertical or horizontal line. Then $C$ is $(A, A)$-invariant if and only if there exist rational functions $U_1, U_2, V_1, V_2$ commuting with $A$ such that the equalities

$$U_1 \circ V_1 = U_2 \circ V_2 = A^d,$$

$$V_1 \circ U_1 = V_2 \circ U_2 = A^d$$

hold for some $d \geq 0$ and the map $t \rightarrow (U_1(t), U_2(t))$ is a parametrization of $C$. \hfill \square

Notice that in general the parametrization $t \rightarrow (U_1(t), U_2(t))$ provided by Theorem 2.4 is not generically one-to-one.
3. Algebraic dependencies between Poincaré functions

Our proof of Theorem 1.1 is based on the results of Section 2 and the lemmas below.

Lemma 3.1. Let $C : f(x, y) = 0$ be an irreducible algebraic curve that admits a parametrization $z \mapsto (\varphi_1(z), \varphi_2(z))$ by functions meromorphic on $C$. Then the desingularization $\tilde{C}$ of $C$ has genus zero or one and there exist meromorphic functions $\varphi : \mathbb{C} \to \tilde{C}$ and $\tilde{\varphi}_1 : \tilde{C} \to \mathbb{CP}^1$, $\tilde{\varphi}_2 : \tilde{C} \to \mathbb{CP}^1$ such that

$$\varphi_1 = \tilde{\varphi}_1 \circ \varphi,$$

$$\varphi_2 = \tilde{\varphi}_2 \circ \varphi,$$

and the map $z \mapsto \tilde{\varphi}_1(z), \tilde{\varphi}_2(z))$ from $\tilde{C}$ to $C$ is generically one-to-one.

Proof. The lemma follows from the Picard theorem (see [1], Theorem 1 and Theorem 2).

Lemma 3.2. Let $A$ be a rational function of degree at least two, and $z_0$ its fixed point with the multiplier $\lambda$. Assume that $W$ is a rational function of degree at least two commuting with $A$ such that $z_0$ is a fixed point of $W$ with the multiplier $\mu$. Then there exist positive integers $l$ and $k$ such that $\mu^l = \lambda^k$.

Proof. By the theorem of Ritt, there exist positive integers $l$ and $k$ such that $W^l = A^k$, and differentiating this equality at $z_0$ we conclude that $\mu^l = \lambda^k$.

Lemma 3.3. Let $A$, $B$ be rational functions of degree at least two, and $X$ a non-constant rational function such that the diagram

$$\begin{array}{ccc}
\mathbb{CP}^1 & \overset{B}{\longrightarrow} & \mathbb{CP}^1 \\
\downarrow & & \downarrow \\
\mathbb{CP}^1 & \overset{A}{\longrightarrow} & \mathbb{CP}^1
\end{array}$$

commutes. Assume that $z_0$ is a fixed point of $B$ with the multiplier $\lambda_0$. Then $z_1 = X(z_0)$ is a fixed point $z_1$ of $A$ with the multiplier

$$\lambda_1 = \lambda_0^{\ord_{z_0} X}.$$

In particular, $z_0$ is repelling if and only if $z_1$ is repelling. Furthermore, if $z_0$ is repelling and $\mathcal{P}_{B,z_0,\lambda}$ is a Poincaré function, then the equality

$$\mathcal{P}_{A,z_1,\lambda_1} (z_0^{\ord_{z_0} X}) = X \circ \mathcal{P}_{B,z_0,\lambda_0}$$

holds for some Poincaré function $\mathcal{P}_{A,z_1,\lambda_1}$.

Proof. It is clear that $z_1$ is a fixed point of $A$, and a local calculation shows that equality (20) holds. Thus, $z_1$ is a repelling fixed point of $A$ if and only if $z_0$ is a repelling fixed point of $B$.

The rest of the proof is obtained by a modification of the proof of the uniqueness of a Poincaré function (see e.g. [12]). Namely, considering the function

$$G = \mathcal{P}_{A,z_1,\lambda_1}^{-1} \circ X \circ \mathcal{P}_{B,z_0,\lambda_0}$$

holomorphic in a neighborhood of zero and satisfying $G(0) = 0$, we see that

$$G(\lambda_0 z) = \mathcal{P}_{A,z_1,\lambda_1}^{-1} \circ X \circ B \circ \mathcal{P}_{B,z_0,\lambda_0} = \mathcal{P}_{A,z_1,\lambda_1}^{-1} \circ A \circ X \circ \mathcal{P}_{B,z_0,\lambda_0} =$$

$$= \lambda_1 \circ \mathcal{P}_{A,z_1,\lambda_1}^{-1} \circ X \circ \mathcal{P}_{B,z_0,\lambda_0} = \lambda_0^{\ord_{z_0} X} G(z).$$
Comparing now coefficients of the Taylor expansions in the left and the right parts of this equality and taking into account that \( \lambda_0 \) is not a root of unity, we conclude that \( G = z^{\text{ord}_{z_0} X} \), implying (21).

**Lemma 3.4.** Let \( A \) be a rational function of degree at least two, \( z_0 \) its repelling fixed point with the multiplier \( \lambda \), and \( P_{A,z_0,\lambda} \) a Poincaré function. Assume that \( C : f(x,y) = 0 \) is an irreducible algebraic curve and \( d_1, d_2 \) are positive integers such that

\[
(22) \quad f \left( P_{A,z_0,\lambda_0}(z^{d_1}), P_{A,z_0,\lambda_0}(z^{d_2}) \right) = 0
\]

holds. Then \( d_1 = d_2 \), and \( C \) is the diagonal \( x = y \).

*Proof.* Substituting \( \lambda_0 z \) for \( z \) into (22), we see that the curve \( C \) is \( (A^{d_1}, A^{d_2}) \)-invariant, and it is clear that \( C \) is not a vertical or horizontal line. Therefore, by Theorem 2.3, there exist non-constant holomorphic maps \( X_1, X_2 : \tilde{C} \to \mathbb{C}P^1 \) and \( B : \tilde{C} \to \mathbb{C}P^1 \) such that the diagram

\[
\begin{array}{ccc}
(\tilde{C})^2 & \xrightarrow{(B,B)} & (\tilde{C})^2 \\
\downarrow (X_1,X_2) & & \downarrow (X_1,X_2) \\
(\mathbb{C}P^1)^2 & \xrightarrow{(A^{d_1}, A^{d_2})} & (\mathbb{C}P^1)^2
\end{array}
\]

commutes. Since this yields that

\[
\deg A^{d_1} = \deg A^{d_2} = \deg B,
\]

we conclude that \( d_1 = d_2 \), implying that \( C \) is the diagonal. \( \square \)

**Corollary 3.5.** Let \( A_1, A_2 \) be rational functions of degree at least two, \( z_1, z_2 \) their repelling fixed points with multipliers \( \lambda_1, \lambda_2 \), and \( P_{A_1,z_1,\lambda_1}, P_{A_2,z_2,\lambda_2} \) Poincaré functions. Assume that \( C : f(x,y) = 0 \) is an irreducible algebraic curve and \( d_1, d_2, \tilde{d}_1, \tilde{d}_2 \) are positive integers such that \( \text{GCD}(d_1, d_2) = 1 \) and the equalities

\[
(23) \quad f \left( P_{A_1,z_1,\lambda_1}(z^{d_1}), P_{A_2,z_2,\lambda_2}(z^{d_2}) \right) = 0,
\]

\[
(24) \quad f \left( P_{A_1,z_1,\lambda_1}(z^{\tilde{d}_1}), P_{A_2,z_2,\lambda_2}(z^{\tilde{d}_2}) \right) = 0
\]

hold. Then there exists a positive integer \( k \) such that the equalities

\[
(25) \quad \tilde{d}_1 = kd_1, \quad \tilde{d}_2 = kd_2
\]

hold.

*Proof.* It is clear that equalities (23), (24) imply the equalities

\[
f \left( P_{A_1,z_1,\lambda_1}(z^{d_1}d_1), P_{A_2,z_2,\lambda_2}(z^{d_2}d_1) \right) = 0
\]

and

\[
f \left( P_{A_1,z_1,\lambda_1}(z^{d_1}\tilde{d}_1), P_{A_2,z_2,\lambda_2}(z^{d_2}\tilde{d}_2) \right) = 0.
\]

Eliminating now from these equalities \( P_{A_1,z_1,\lambda_1}(z^{d_1}d_1) \), we conclude that the functions \( P_{A_2,z_2,\lambda_2}(z^{d_2}d_1) \) and \( P_{A_2,z_2,\lambda_2}(z^{d_1}d_2) \) are algebraically dependent. Therefore, \( \tilde{d}_1d_2 = d_1\tilde{d}_2 \) by Lemma 3.4, implying (25). \( \square \)
Proof of Theorem 1.4 Let $C : f(x, y) = 0$ be an irreducible algebraic curve with a generically one-to-one parametrization by rational functions $z \to (X_1(z), X_2(z))$, and $d_1$, $d_2$ coprime positive integers. Assume that diagram (8) commutes for some rational function $B$ with a repelling fixed point $z_0$ and equalities (9), (10) hold. Then denoting the multiplier of $z_0$ by $\lambda$ and using Lemma 3.3 we see that

$$\lambda_{i_1}^0 = \lambda^{ord_{z_0} X_1}, \quad \lambda_{i_2}^0 = \lambda^{ord_{z_0} X_2},$$

and

$$0 = f(X_1, X_2) = f(\mathcal{P}_{B, z_0, \lambda} \circ X_1, \mathcal{P}_{B, z_0, \lambda} \circ X_2) = f\left(\mathcal{P}_{A_1, z_1, \lambda_{i_1}^0} \left(z^{ord_{z_0} X_1}\right), \mathcal{P}_{A_2, z_2, \lambda_{i_2}^0} \left(z^{ord_{z_0} X_2}\right)\right).$$

Since

$$\mathcal{P}_{A_1, z_1, \lambda_{i_1}^0} (z) = \mathcal{P}_{A_1, z_1, \lambda} (z), \quad \mathcal{P}_{A_2, z_2, \lambda_{i_2}^0} (z) = \mathcal{P}_{A_2, z_2, \lambda} (z),$$

this implies that

$$f\left(\mathcal{P}_{A_1, z_1, \lambda} \left(z^{ord_{z_0} X_1}\right), \mathcal{P}_{A_2, z_2, \lambda} \left(z^{ord_{z_0} X_2}\right)\right) = 0.$$

Finally, (10) implies that if (27) holds, then (4) also holds. This proves the “if” part of the theorem.

To prove the “only if” part, it is enough to show that equality (7) implies that there exist positive integers $r_1, r_2$ such that

$$\lambda_{i_1}^{r_1} = \lambda_{i_2}^{r_2} = \lambda.$$

Indeed, in this case substituting $\lambda z$ for $z$ into (7) we obtain the equality

$$f\left(A_{1}^{ord_{z_0} X_1} \circ \mathcal{P}_{A_1, z_1, \lambda_{i_1}^0} \left(z^{d_1}\right), A_{2}^{ord_{z_0} X_2} \circ \mathcal{P}_{A_2, z_2, \lambda_{i_2}^0} \left(z^{d_2}\right)\right) = 0.$$

Therefore, for

$$l_1 = d_1 r_1, \quad l_2 = d_2 r_2,$

the curve $C$ is $(A_{1}^{l_1}, A_{2}^{l_2})$-invariant, implying by Theorem 2.3 that $C$ has genus zero and there exist rational functions $X_1, X_2$ and $B$ such that diagram (8) commutes and the map $z \to (X_1(z), X_2(z))$ is a generically one-to-one parametrization of $C$.

Further, it follows from Lemma 3.1 that there exists a meromorphic function $\varphi$ such that the equalities

$$\mathcal{P}_{A_1, z_1, \lambda_{i_1}^0} (z^{d_1}) = X_1 \circ \varphi(z), \quad \mathcal{P}_{A_2, z_2, \lambda_{i_2}^0} (z^{d_2}) = X_2 \circ \varphi(z),$$

hold. Thus,

$$z_1 = \mathcal{P}_{A_1, z_1, \lambda_{i_1}^0} (0) = X_1 \circ \varphi(0), \quad z_2 = \mathcal{P}_{A_2, z_2, \lambda_{i_2}^0} (0) = X_2 \circ \varphi(0),$$

implying that equalities (9) hold for the point $z_0 = \varphi(0)$.

Since $z_1$ and $z_2$ are fixed points of $A_1$ and $A_2$, the point $z_0$ is a preperiodic point of $B$. Thus, changing in (8) the functions $B$ and $A_{1}^{l_1}, A_{2}^{l_2}$ to some of their iterates, and the point $z_0$ to some point in its $B$-orbit, we may assume that $z_0$ is a fixed point of $B$. Moreover, $z_0$ is repelling by Lemma 3.3. Finally, using the “if” part of the theorem, we see that equalities (7) and (27) hold simultaneously, implying by Corollary 5.5 that equalities (10) hold.
Let us show now that (7) implies (28). Assume first that \( A_1 \) and \( A_2 \) are not generalized Lattès maps. Substituting \( \lambda_2 z \) for \( z \) into equality (7) we obtain the equality

\[
f(P_{A_1,z_1,\lambda_1} \circ (\lambda_2 z)^{d_1}, P_{A_2,z_2,\lambda_2} \circ (\lambda_2 z)^{d_2}) =
\]

\[
= f(P_{A_1,z_1,\lambda_1} \circ (\lambda_2 z)^{d_1}, A_2^{q d_2} \circ P_{A_2,z_2,\lambda_2} \circ z^{d_2}) = 0,
\]

implying that the functions \( P_{A_1,z_1,\lambda_1} \circ (\lambda_2 z)^{d_1} \) and \( P_{A_2,z_2,\lambda_2} \circ z^{d_2} \) satisfy the equality

\[
(29)\quad g(P_{A_1,z_1,\lambda_1} \circ (\lambda_2 z)^{d_1}, P_{A_2,z_2,\lambda_2} \circ z^{d_2}) = 0,
\]

where \( g(x, y) = f(x, A_2^{q d_2}(y)) \). Eliminating now from (7) and (29) the function \( P_{A_2,z_2,\lambda_2} \circ z^{d_2} \), we conclude that the functions \( P_{A_1,z_1,\lambda_1} \circ (\lambda_2 z)^{d_1} \) and \( P_{A_1,z_1,\lambda_1} \circ (\lambda_2 z)^{d_1} \) are algebraically dependent. In turn, this implies that the functions \( P_{A_1,z_1,\lambda_1}(z) \) and \( P_{A_1,z_1,\lambda_1}(\lambda_2^{d_1} z) \) also are algebraically dependent.

Let \( \tilde{C} : f(x, y) = 0 \) be a curve such that

\[
\tilde{f}(P_{A_1,z_1,\lambda_1}(z), P_{A_1,z_1,\lambda_1}(\lambda_2^{d_1} z)) = 0.
\]

Then substituting \( \lambda_1 z \) for \( z \) we see that \( \tilde{f} \) is \( (A_1, A_1) \)-invariant. Therefore, by Theorem 23 there exist rational function \( V_1 \) and \( V_2 \) commuting with \( A_1 \) such that \( \tilde{C} \) is a component of the curve

\[
V_1(x) - V_2(y) = 0,
\]

implying that the equality

\[
(30)\quad V_1 \circ P_{A_1,z_1,\lambda_1}(z) = V_2 \circ P_{A_1,z_1,\lambda_1}(\lambda_2^{d_1} z)
\]

holds. Furthermore, it follows from the Ritt theorem that there exist positive integers \( s_1, s_2 \), and \( s \) such that

\[
(31)\quad V_1^{\circ s_1} = V_2^{\circ s_2} = A_1^{\circ s}.
\]

Since (30) implies that for every \( l \geq 1 \) the equality

\[
V_1^{\circ l} \circ V_1 \circ P_{A_1,z_1,\lambda_1}(z) = V_1^{\circ l} \circ V_2 \circ P_{A_1,z_1,\lambda_1}(\lambda_2^{d_1} z)
\]

holds, setting

\[
W_1 = V_1^{\circ s_1}, \quad W_2 = V_1^{\circ (s_1-1)} \circ V_2,
\]

we see that \( W_1 \) and \( W_2 \) also commute with \( A_1 \) and satisfy

\[
(32)\quad W_1 \circ P_{A_1,z_1,\lambda_1}(z) = W_2 \circ P_{A_1,z_1,\lambda_1}(\lambda_2^{d_1} z).
\]

In addition, \( z_1 \) is a fixed point of \( W_1 \) by (31). Finally, since equality (32) implies the equality

\[
W_1(z_1) = W_2(z_1),
\]

the point \( z_1 \) is also a fixed point of \( W_2 \).

Differentiating equality (32) at zero, we see that the multipliers

\[
\mu_1 = W'_1(z_1), \quad \mu_2 = W'_2(z_1)
\]

satisfy the equality

\[
(33)\quad \mu_1 = \mu_2 \lambda_2^{d_1}.
\]
On the other hand, Lemma 3.2 yields that there exist positive integer \( k_1 \), \( k_2 \), and \( k \) such that

\[
\mu_1^{k_1} = \mu_2^{k_2} = \lambda_1^k.
\]

It follows now from (33) and (34) that

\[
\lambda_1^{k_{k_2}} = \mu_1^{k_{k_2}} = \mu_2^{k_{k_2}} \lambda_2^{d_{k_1}k_{k_2}} = \lambda_1^{k_{k_1}} \lambda_2^{d_{k_1}k_{k_2}},
\]

implying that

\[
\lambda_1^{k(k_2-k_1)} = \lambda_2^{d_{k_1}k_{k_2}}.
\]

Moreover, since \(|\lambda_1| > 1, |\lambda_2| > 1\), the number \( k_2 - k_1 \) is positive. This proves the implication (47) \( \Rightarrow \) (48) in case \( A_1 \) and \( A_2 \) are not generalized Lattès maps.

Finally, assume that \( A_1, A_2 \) are arbitrary non-special rational functions. Then, by Theorem 2.2 there exist rational functions \( F_1, F_2, \theta_1, \theta_2 \) such that the diagrams

\[
\begin{array}{ccc}
C & \xrightarrow{F_1} & C \\
\downarrow \theta_1 & & \downarrow \theta_2 \\
\mathbb{C}P^1 & \xrightarrow{A_1} & \mathbb{C}P^1 \\
\end{array}
\]

commute, and \( F_1, F_2 \) are not generalized Lattès maps. Further, since all the points in the preimage \( \theta_{A_1}^{-1}(z_i), i = 1, 2, \) are \( F_i \)-preperiodic, there exist a positive integer \( N \) and fixed points \( z'_1, z'_2 \) of \( F_1^N, F_2^N \) such that the diagrams

\[
\begin{array}{ccc}
C & \xrightarrow{F_1^N} & C \\
\downarrow \theta_1 & & \downarrow \theta_2 \\
\mathbb{C}P^1 & \xrightarrow{A_1^N} & \mathbb{C}P^1 \\
\end{array}
\]

commute, and the equalities

\[
\theta_1(z'_1) = z_1, \quad \theta_1(z'_2) = z_2
\]

hold. Moreover, if \( \mu_i, i = 1, 2, \) is the multiplier of \( z'_i, i = 1, 2, \) then, by Lemma 3.3 the equalities

\[
\mu_1^{\text{ord}_{z'_1} \theta_1} = \lambda_1^N, \quad \mu_2^{\text{ord}_{z'_2} \theta_2} = \lambda_2^N,
\]

(35)

\[
\mathcal{P}_{A_1^N, z_1, \lambda_1}^N(z^{\text{ord}_{z'_1} \theta_1}) = \theta_1 \circ \mathcal{P}_{F_1^N, z'_1, \mu_1}(z),
\]

(36)

\[
\mathcal{P}_{A_2^N, z_2, \lambda_2}^N(z^{\text{ord}_{z'_2} \theta_2}) = \theta_2 \circ \mathcal{P}_{F_2^N, z'_2, \mu_2}(z)
\]

(37)

hold.

Setting

\[
f_1 = \text{ord}_{z'_1} \theta_1, \quad f_2 = \text{ord}_{z'_2} \theta_2, \quad f = f_1 f_2,
\]

and substituting \( z^{d_1 f_2} \) and \( z^{d_2 f_1} \) for \( z \) into equalities (36) and (37), we obtain that

\[
\mathcal{P}_{A_1, z_1, \lambda_1}(z^{d_1 f_2}) = \mathcal{P}_{A_1^N, z_1, \lambda_1}(z^{d_1 f}) = \theta_1 \circ \mathcal{P}_{F_1^N, z'_1, \mu_1}(z^{d_1 f_2}),
\]

\[
\mathcal{P}_{A_2, z_2, \lambda_2}(z^{d_2 f_1}) = \mathcal{P}_{A_2^N, z_2, \lambda_2}(z^{d_2 f}) = \theta_2 \circ \mathcal{P}_{F_2^N, z'_2, \mu_2}(z^{d_2 f_1}).
\]
Thus, equality (7) implies that the functions \( P_{F_1^N, z_1', \mu_1}(z^{d_1}f_2) \) and \( P_{F_2^N, z_2', \mu_2}(z^{d_2}f_1) \) satisfy the equality
\[
\tilde{f}\left(P_{F_1^N, z_1', \mu_1}(z^{d_1}f_2), P_{F_2^N, z_2', \mu_2}(z^{d_2}f_1)\right) = 0,
\]
where
\[
\tilde{f}(x, y) = f(\theta_1(x), \theta_2(y)).
\]
Since \( F_1^N, F_2^N \) are not generalized Lattès maps, by what is proved above, there exist positive integers \( p_1, p_2 \) such that \( \mu_1^{p_1} = \mu_2^{p_2} \), implying by (26) that
\[
\lambda_1^{p_1}f_1^N = \mu_1^{p_1}f_1 = \mu_2^{p_2}f_2 = \lambda_2^{p_2}f_1^N.
\]
Thus, equality (28) holds for the integers
\[
r_1 = p_1f_2N, \quad r_2 = p_2f_1N.
\]
\( \square \)

**Proof of Corollary 1.2.** If \( P_{A_1, z_1, \lambda_1}, P_{A_2, z_2, \lambda_2} \) are algebraically dependent, then it follows from the commutativity of diagram (33) that
\[
(deg A_1)^{l_1} = (deg A_2)^{l_2} = deg B,
\]
implying that \( n_1^{l_1} = n_2^{l_2} \).
On the other hand, it follows from equalities (26) that
\[
\lambda_1^{l_1\text{ord}_{l_1}X_2} = \lambda_2^{l_2\text{ord}_{l_2}X_1}.
\]
\( \square \)

The following result shows that if \( A_1 \) and \( A_2 \) are not generalized Lattès maps, then dependencies (7) actually reduce to dependencies (1).

**Theorem 3.6.** Let \( A_1, A_2 \) be rational functions of degree at least two that are not generalized Lattès maps, \( z_1, z_2 \) their repelling fixed points with multipliers \( \lambda_1, \lambda_2 \), and \( P_{A_1, z_1, \lambda_1}, P_{A_2, z_2, \lambda_2} \) Poincaré functions. Assume that \( C : f(x, y) = 0 \) is an irreducible algebraic curve, and \( d_1, d_2 \) are coprime positive integers such that the equality

\[
\tilde{f}\left(P_{A_1, z_1, \lambda_1}(z^{d_1}), P_{A_2, z_2, \lambda_2}(z^{d_2})\right) = 0
\]

holds. Then \( d_1 = d_2 = 1 \) and \( C \) has genus zero. Furthermore, if \( C : f(x, y) = 0 \) is an irreducible curve of genus zero with a generically one-to-one parametrization by rational functions \( z \rightarrow (X_1(z), X_2(z)) \), then the equality

\[
f(P_{A_1, z_1, \lambda_1}(z), P_{A_2, z_2, \lambda_2}(z)) = 0
\]
holds for some Poincaré functions \( P_{A_1, z_1, \lambda_1}, P_{A_2, z_2, \lambda_2} \) if and only if there exist positive integers \( l_1, l_2, k \) and a rational function \( B \) with a repelling fixed point \( z_0 \) such that the diagram

\[
\begin{array}{ccc}
(CP^1)^2 & \overset{(B, B)}{\rightarrow} & (CP^1)^2 \\
(X_1, X_2) \downarrow & & \downarrow (X_1, X_2) \\
(CP^1)^2 & \overset{(A^{l_1}_1, A^{l_2}_2)}{\rightarrow} & (CP^1)^2,
\end{array}
\]

commutes, and the equalities

\[
X_1(z_0) = z_1, \quad X_2(z_0) = z_2
\]
hold.
Proof. If $A_1, A_2$ are not generalized Lattès maps, then it follows from the commutativity of diagram (8) by Proposition 2.1 that there exist rational functions $Y_1$ and $Y_2$ such that the equalities

$$Y_1 \circ X_1 = B^{d_1}, \quad Y_2 \circ X_2 = B^{d_2},$$

hold for some $d_1, d_2 \geq 0$. Therefore, for any repelling fixed point $z_0$ of $B$,

$$X_1'(z_0) \neq 0, \quad X_2'(z_0) \neq 0$$

by the chain rule. Thus, $d_1 = d_2 = k = 1$ by (10).

Notice that in distinction with the case of Böttcher functions, algebraic dependencies (1) of degree greater than one between Poincaré functions do exist. The simplest of them are graphs constructed as follows. Let us take any two rational functions $U$ and $V$, and set

$$(38) \quad A_1 = U \circ V, \quad A_2 = V \circ U.$$ 

Then the diagram

$$\begin{array}{ccc}
\mathbb{CP}^1 & \xrightarrow{A_1} & \mathbb{CP}^1 \\
V \downarrow & & \downarrow V \\
\mathbb{CP}^1 & \xrightarrow{A_2} & \mathbb{CP}^1 
\end{array}$$

obviously commutes. Moreover, if $z_0$ is a repelling fixed point of $A_1$, then the point $z_1 = V(z_0)$ is a repelling fixed point of $A_2$ by Lemma 3.3. Finally, the first equality in (38) implies that $V'(z_1) \neq 0$. Therefore,

$$P_{A_2, \lambda_2, \lambda_2} = V \circ P_{A_1, \lambda_1, \lambda_1},$$

by Lemma 3.3.

Notice also that the equality $d_1 = d_2$ provided by Theorem 3.6 does not hold for arbitrary non-special $A_1, A_2$. For example, let $A$ be any rational function of the form $A = zR^d(z)$, where $R \in \mathbb{C}(z)$ and $d > 1$. Then one can easily check that $A : \emptyset \to \emptyset$, where $\emptyset$ is defined by the equalities

$$\nu(0) = d, \quad \nu(\infty) = d,$$

is a minimal holomorphic map between orbifolds. Thus, $A$ is a generalized Lattès. Furthermore, the diagram

$$\begin{array}{ccc}
\mathbb{CP}^1 & \xrightarrow{zR^d(z)} & \mathbb{CP}^1 \\
\downarrow z^d & & \downarrow z^d \\
\mathbb{CP}^1 & \xrightarrow{zR^d(z)} & \mathbb{CP}^1, 
\end{array}$$

obviously commutes, and it is clear that we can choose $R$ in such a way that zero is a repelling fixed point of $zR^d(z)$. Denoting now by $\lambda$ the multiplier of $zR^d(z)$ at zero, we obtain by Lemma 3.3 that

$$P_{zR^d(z), 0, \lambda^d} = z^d \circ P_{zR^d(z), 0, \lambda}.$$ 

Thus, $P_{zR^d(z), 0, \lambda^d}(z^d)$ and $P_{zR^d(z), 0, \lambda}(z)$ are algebraically dependent.
4. Algebraic dependencies between Böttcher functions

4.1. Polynomial semiconjugacies and invariant curves. If $A_1, A_2$ are non-special polynomials of degree at least two, then any irreducible $(A_1, A_2)$-invariant curve $C$ that is not a vertical or horizontal line has genus zero and allows for a generically one-to-one parametrization by polynomials $X_1, X_2$ such that the diagram

\[
\begin{array}{ccc}
\mathbb{CP}^1 \times \mathbb{CP}^1 & \xrightarrow{(B, B)} & \mathbb{CP}^1 \\
(X_1, X_2) & \downarrow & (X_1, X_2) \\
\mathbb{CP}^1 \times \mathbb{CP}^1 & \xrightarrow{(A_1, A_2)} & \mathbb{CP}^1
\end{array}
\]

(39)

commutes for some polynomial $B$ (see Proposition 2.34 of [11] or Section 4.3 of [17]).

For fixed polynomials $A, B$ of degree at least two, we denote by $E(A, B)$ the set (possibly empty) consisting of polynomials $X$ of degree at least two such that diagram (19) commutes. The following result was proved in the paper [17] as a corollary of results of the paper [15].

**Theorem 4.1.** Let $A$ and $B$ be fixed non-special polynomials of degree at least two such that the set $E(A, B)$ is non-empty, and let $X_0$ be an element of $E(A, B)$ of the minimum possible degree. Then a polynomial $X$ belongs to $E(A, B)$ if and only if $X = \tilde{A} \circ X_0$ for some polynomial $\tilde{A}$ commuting with $A$. □

Notice that applying Theorem 4.1 for $B = A$ one can reprove the classification of commuting polynomials and, more generally, of commutative semigroups of $\mathbb{C}[z]$ obtained in the papers [26], [28], [5] (see [25], Section 7.1, for more detail). On the other hand, applying Theorem 4.1 to system (39) with $A_1 = A_2 = A$, we see that $X_1, X_2$ cannot provide a generically one-to-one parametrization of $C$, unless one of the polynomials $X_1, X_2$ has degree one. Moreover if, say, $X_1$ has degree one, then without loss of generality we may assume that $X_1 = z$, implying that $X_2$ commutes with $A$. Thus, we obtain the following result obtained by Medvedev and Scanlon in the paper [11].

**Theorem 4.2.** Let $A$ be a non-special polynomial of degree at least two, and $C$ an irreducible algebraic curve that is not a vertical or horizontal line. Then $C$ is $(A, A)$-invariant if and only if $C$ has the form $x = P(y)$ or $y = P(x)$, where $P$ is a polynomial commuting with $A$. □

Finally, yet another corollary of Theorem 4.1 is the following result, which complements the classification of $(A_1, A_2)$-invariant curves obtained in [11] (see [17], Theorem 1.4).

**Theorem 4.3.** Let $A_1, A_2$ be non-special polynomials of degree at least two, and $C$ a curve. Then $C$ is an irreducible $(A_1, A_2)$-invariant curve if and only if $C$ has the form $Y_1(x) - Y_2(y) = 0$, where $Y_1, Y_2$ are polynomials of coprime degrees satisfying the equations

$$T \circ Y_1 = Y_1 \circ A_1, \quad T \circ Y_2 = Y_2 \circ A_2$$

for some polynomial $T$. □
4.2. Proof of Theorem 1.3

As in the case of Poincaré functions, we do not assume that considered Böttcher functions are normalized. Thus, the notation $\mathcal{B}_P$ is used to denote some function satisfying conditions (4), (5).

To prove Theorem 1.3 we need the following two lemmas.

**Lemma 4.4.** Let $A$, $B$ be polynomials of degree at least two, and $X$ a non-constant polynomial such that the diagram

$$
\begin{array}{ccc}
\mathbb{CP}^1 & \xrightarrow{B} & \mathbb{CP}^1 \\
\downarrow X & & \downarrow X \\
\mathbb{CP}^1 & \xrightarrow{A} & \mathbb{CP}^1
\end{array}
$$

commutes. Assume that $\mathcal{B}_B$ is a Böttcher function. Then

$$X \circ \mathcal{B}_B(z) = \mathcal{B}_A(z^{\deg X})$$

for some Böttcher function $\mathcal{B}_A$.

**Proof.** The lemma follows from Lemma 2.1 of [14]. □

**Lemma 4.5.** Let $A$ be a polynomial of degree $n \geq 2$, and $\mathcal{B}_A$ a Böttcher function. Assume that $C : f(x, y) = 0$ is an irreducible algebraic curve and $d_1, d_2$ are positive integers such that $d_1 \leq d_2$ and the equality

$$f(\mathcal{B}_A(z^{d_1}), \mathcal{B}_A(z^{d_2})) = 0$$

holds. Then $C$ is a graph

$$P(x) - y = 0,$$

where $P$ is a polynomial commuting with $A$, and the equality

$$d_1 \deg P = d_2$$

holds.

**Proof.** Substituting $z^n$ for $z$ in (10), we see that the curve $C$ is $(A, A)$-invariant. Therefore, by Theorem 1.2 $C$ is a graph of the form $x = P(y)$ or $y = P(x)$, where $P$ is a polynomial commuting with $A$. Taking into account that $d_1 \leq d_2$, this implies that (11) and (12) hold. □

**Corollary 4.6.** Let $A_1$, $A_2$ be polynomials of degree at least two, and $\mathcal{B}_{A_1}$, $\mathcal{B}_{A_2}$ Böttcher functions. Assume that $C : f(x, y) = 0$ is an irreducible algebraic curve of genus zero and $d_1, d_2, \tilde{d}_1, \tilde{d}_2$ are positive integers such that $\gcd(d_1, d_2) = 1$ and the equalities

$$f(\mathcal{B}_{A_1}(z^{d_1}), \mathcal{B}_{A_2}(z^{d_2})) = 0,$$

$$f(\mathcal{B}_{A_1}(z^{\tilde{d}_1}), \mathcal{B}_{A_2}(z^{\tilde{d}_2})) = 0$$

hold. Then there exists a positive integer $k$ such that the equalities

$$\tilde{d}_1 = kd_1, \quad \tilde{d}_2 = kd_2$$

hold.
Proof. It is clear that equalities (43), (44) imply the equalities
\[
(46) \quad f\left(B_{A_1}(z^{d_1}), B_{A_2}(z^{d_2})\right) = 0
\]
and
\[
(47) \quad f\left(B_{A_1}(z^{d_1}), B_{A_2}(z^{d_2})\right) = 0,
\]
and eliminating from these equalities the function \(B_{A_1}(z^{d_1})\), we conclude that the functions \(B_{A_2}(z^{d_2})\) and \(B_{A_2}(z^{d_1})\) are algebraically dependent. Therefore, by Lemma 4.5, one of these functions is a polynomial in the other.

Assume, say, that
\[
(48) \quad B_{A_2}(z^{d_2}) = R \circ B_{A_2}(z^{d_2})
\]
(the other case is considered similarly). Then substituting the right part of this equality for the left part into (46), we conclude that
\[
f\left(B_{A_1}(z^{d_1}), R \circ B_{A_2}(z^{d_2})\right) = 0,
\]
implying that
\[
(49) \quad f\left(B_{A_1}(z^{d_1}), R \circ B_{A_2}(z^{d_2})\right) = 0,
\]
Let us observe now that equalities (44) and (48) imply that the curve \(f(x, y) = 0\) is invariant under the map
\[
(z_1, z_2) \to (\hat{A}_1(z_1), \hat{A}_2(z_2)) = (z_1, R(z_2)).
\]
Since the commutativity of (49) implies that \(\deg A_1 = \deg A_2\), this yields that \(\deg R = 1\). It follows now from (47) that
\[
d_2 \hat{d}_1 = d_1 \hat{d}_2,
\]
implying (45). □

Proof of Theorem 1.3. The “if” part of the theorem and the implication (11) ⇒ (12) are proved in [14]. For the reader convenience we reproduce the proof below.

The “if” part follows from Lemma 4.4. On the other hand, setting \(n_1 = \deg A_1\), \(n_2 = \deg A_2\), and substituting \(z^{n_2}\) for \(z\) into (11) we obtain the equality
\[
(50) \quad f(B_{A_1}(z^{d_1}), A_2 \circ B_{A_2}(z^{d_2})) = 0.
\]
Eliminating now \(B_{A_2}(z^{d_2})\) from (11) and (49), we conclude that the functions \(B_{A_1}(z^{d_1})\) and \(B_{A_1}(z^{d_1})\) are algebraically dependent. Since the corresponding algebraic curve \(\bar{f}(x, y) = 0\) such that
\[
\bar{f}(B_{A_1}(z^{d_1}), B_{A_1}(z^{d_1})) = 0
\]
is \((A_1, A_1)\)-invariant, it follows from Theorem 4.2 that
\[
(51) \quad B_{A_1}(z^{d_1}) = P \circ B_{A_1}(z^{d_1})
\]
for some polynomial \(P\) commuting with \(A_1\). Clearly, equality (51) implies that \(\deg P = n_2\). On the other hand, by the Ritt theorem, \(P\) and \(A_1\) have a common iterate. Therefore, there exist positive integers \(l_1, l_2\) such \(n_1^{l_1} = n_2^{l_2}\). Setting now
\[
n = n_1^{l_1} = n_2^{l_2}
\]
and substituting $z^n$ for $z$ into (11) we obtain that $f(x, y)$ is $(A_1^{d_1}, A_2^{d_2})$-invariant, implying that (12) holds.

To finish the proof we only must show that equalities (13) hold. For this purpose, we observe that a generically one-to-one parametrization $z \rightarrow (X_1(z), X_2(z))$ of the curve

$$Y_1(x) - Y_2(y) = 0$$

satisfies the conditions

$$\deg X_1 = \deg Y_2, \quad \deg X_2 = \deg Y_1.$$ 

Therefore, Theorem 4.3 yields that the degrees

$$\deg X_1 = d'_1, \quad \deg X_2 = d'_2$$

of the functions $X_1$ and $X_2$ in (12) satisfy $\gcd(d'_1, d'_2) = 1$. Using now the “if” part of the theorem, we see that equalities (11) and

$$f(B_{A_1}(z^{d'_1}), B_{A_2}(z^{d'_2})) = 0$$

hold simultaneously, implying by Corollary 4.6 that equalities (13) hold. □

References


Department of Mathematics, Ben Gurion University of the Negev, Israel

Email address: pakovich@math.bgu.ac.il