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Author
Nguyen, Khoa Dang

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Arithmetic Dynamics of Diagonally Split Polynomial Maps

by

Khoa Dang Nguyen

A dissertation submitted in partial satisfaction of the requirements for the degree of Doctor of Philosophy in Mathematics in the Graduate Division of the University of California, Berkeley

Committee in charge:

Professor Thomas Scanlon, Co-chair
Professor Paul Vojta, Co-chair
Professor Mary K. Gaillard

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Arithmetic Dynamics of Diagonally Split Polynomial Maps

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Abstract

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Doctor of Philosophy in Mathematics

University of California, Berkeley

Professor Thomas Scanlon, Co-chair

Professor Paul Vojta, Co-chair

Let $K$ be a number field or the function field of a curve over an algebraically closed field of characteristic 0. Let $n \geq 2$, and let $f(X) \in K[X]$ be a polynomial of degree $d \geq 2$. We present two arithmetic properties of the dynamics of the coordinate-wise self-map $\varphi = f \times \ldots \times f$ of $(\mathbb{P}^1)^n$, namely the dynamical analogs of the Hasse principle and the Bombieri-Masser-Zannier height bound theorem. In particular, we prove that the Hasse principle holds when we intersect an orbit and a preperiodic subvariety, and that the intersection of a curve with the union of all periodic hypersurfaces have bounded heights unless that curve is vertical or contained in a periodic hypersurface. A common crucial ingredient for the proof of these two properties is a recent classification of $\varphi$-periodic subvarieties by Medvedev-Scanlon. We also present the problem of primitive prime divisors in dynamical sequences by Ingram-Silverman which is needed and closely related to the dynamical Hasse principle. Further questions on the bounded height result, and a possible generalization of the Medvedev-Scanlon classification are briefly given at the end.
To my parents and my wife for their tremendous support during my graduate study and beyond...
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This thesis mainly follows the paper [34] to appear in International Mathematics Research Notices published by Oxford University Press. This paper [34] uses or is motivated by results in the joint papers [19], and [1]. I wish to thank my collaborators of [19], and [1]: Chad Gratton, Thomas Tucker, Ekaterina Amerik, Pär Kurlberg, Adam Towsley, Bianca Viray, and Felipe Voloch for the opportunities to learn from them.

I wish to dedicate this thesis to my parents and my wife. Their endless support helped me overcome the most depressing moment of my graduate study.
Chapter 1

Introduction

A discrete dynamical system is a set $S$ together with a map $\varphi$ from $S$ to itself, and dynamics is the study of the family of iterates $\{\varphi, \varphi^2, \ldots\}$. The situation becomes much more interesting when $S$ is a variety and $\varphi$ is a morphism defined over a field $K$. Complex dynamists are interested in the case $K = \mathbb{C}$ with seminal work by Fatou and Julia on rational self-maps of the projective line. On the other hand, arithmetic dynamists are interested in the number-theoretic properties of the system $\{\varphi, \varphi^2, \ldots\}$ when $K$ is a number field. For an introduction to these rapidly evolving subjects, we refer the readers to the books of Milnor [32] and Silverman [42].

In this thesis, we present two results in the arithmetic dynamics of diagonally split polynomial maps obtained by the author [34]. Let $n \geq 2$, by a diagonally split polynomial self-map of $(\mathbb{P}^1)^n$, we mean the coordinate-wise self-map $\varphi = f \times \ldots \times f$ where $f(X)$ is a polynomial of degree $d \geq 2$. When $f(X)$ is linear conjugate to $X^d$, or $\pm C_d(X)$, where $C_d(X)$ is the Chebyshev polynomial of degree $d$ (i.e. the unique polynomial of degree $d$ such that $C_d(X + \frac{1}{X}) = X^d + \frac{1}{X^d}$), the map $\varphi$ “essentially comes from” the multiplication-by-$d$ map on the torus $\mathbb{G}_m^n$. Therefore the arithmetic dynamics of $\varphi$ provides a dynamical analogue of the arithmetic of $\mathbb{G}_m^n$ which is an active area of research, for examples, see [49]. More specifically, we prove a Hasse principle and an analogue of the Bombieri-Masser-Zannier height bound theorem [10] for the dynamics of $\varphi$. The main ingredient is a classification of $\varphi$-periodic subvarieties of $(\mathbb{P}^1)^n$ obtained recently by Medvedev and Scanlon [31].

For the rest of this thesis, let $K$ be a number field or the function field of a curve over an algebraically closed field of characteristic zero. Our first main result is called the (strong) dynamical Hasse principle in [1], as follows. We are given a projective variety $X$, a self-map $\phi$ of $X$, a closed subvariety $V$ of $X$, all defined over $K$. We are given a $K$-rational point $P \in X(K)$ such that the $\phi$-orbit:

$$\mathcal{O}_\phi(P) := \{P, \phi(P), \ldots\}$$

does not intersect $V(K)$. Under certain extra conditions, one may ask if there are infinitely many primes $p$ of $K$ such that the $p$-adic closure of $\mathcal{O}_\phi(P)$ does not intersect $V(K_p)$. This is the same as requiring that modulo $p^m$ for sufficiently large $m$ the orbit of $P$ does not intersect
CHAPTER 1. INTRODUCTION

V. This kind of question was first investigated by Hsia and Silverman [25] with motivation from the Brauer-Manin obstruction to the Hasse principle in diophantine geometry. We refer the readers to [25] and the references there for more details. As far as we know, all the previous papers treating the dynamical Hasse principle so far either assume that \( \dim(V) = 0 \) [43], [7], or that \( \phi \) is étale [25], [1]. By combining results and techniques in [43] and [1] in addition to the Medvedev-Scanlon theorem, we are able to give examples when \( \dim(V) > 0 \) and \( \phi \) is not étale (see [34, Theorem 1.1]):

**Theorem 1.1.** Let \( f(X) \) be a polynomial of degree \( d \geq 2 \) in \( K[X] \), and \( \phi = f \times \ldots \times f : (\mathbb{P}^1_K)^n \to (\mathbb{P}^1_K)^n \). Let \( V \) be an absolutely irreducible \( \phi \)-preperiodic curve or hypersurface in \( (\mathbb{P}^1_K)^n \), and \( P \in (\mathbb{P}^1)^n(K) \) such that the \( \phi \)-orbit of \( P \) does not intersect \( V(K) \). Then there are infinitely many primes \( p \) of \( K \) such that the \( p \)-adic closure of the orbit of \( P \) does not intersect \( V(K_p) \), where \( K_p \) is the \( p \)-adic completion of \( K \).

Our second main result should be called the dynamical Bombieri-Masser-Zannier height bound. With motivation from the Manin-Mumford conjecture, Lang asks whether a curve in \( \mathbb{G}_m^n \) that is not a torsion translate of a subgroup has only finitely many torsion points, and an affirmative answer has been given by Ihara, Serre and Tate independently. In the original paper [10, Theorem 1], Bombieri, Masser and Zannier proceed further by investigating the question of “complementary dimensional intersections”, such as the intersection of a curve that is not contained in a translate of a subgroup with torsion translates of subgroups of codimension one. Recently, a dynamical analogue of the Manin-Mumford conjecture and Lang’s question has been proposed by Zhang [50], and modified by Zhang, Ghioca and Tucker [17]. However, as far as we know, a dynamical “complementary dimensional intersection” analogue of the Bombieri-Masser-Zannier theorem has not been treated before. By applying the Medvedev-Scanlon theorem and basic (canonical) height arguments, we establish such a dynamical analogue (see [34, Theorem 1.2]):

**Theorem 1.2.** Let \( f(X) \), \( d \), and \( \phi \) be as in Theorem 1.1. Assume that \( f(X) \) is not linearly conjugate to \( X^d \) or \( \pm C_d(X) \). Let \( C \) be an irreducible curve in \( (\mathbb{P}^1_K)^n \) that is not contained in any \( \phi \)-periodic hypersurface. Assume that \( C \) maps surjectively onto each factor \( \mathbb{P}^1 \) of \( (\mathbb{P}^1)^n \). Then the set of points

\[
\bigcup_{V} (C(K) \cap V(K))
\]

has bounded height, where \( V \) ranges over all \( \phi \)-periodic hypersurfaces of \( (\mathbb{P}^1_K)^n \).

The above two theorems are examples of the main results and topics presented in this thesis. We refer the readers to Theorems 4.5, 4.6, 4.7, 5.3, 5.12, 5.13, and 5.17 for much more general results. This thesis mainly follows our paper [34] together with a presentation of some results in [19] and [1] that are either needed or related to the main problems considered here.

The organization of this thesis is as follows. First, we introduce the problem on the existence of primitive prime divisors in dynamical sequences. This includes an unconditional
result of Ingram and Silverman [27] in a special case which will be needed in our proof of Theorem 1.1, as well as our result in the general case conditionally on the ABC Conjecture obtained jointly with Chad Gratton and Thomas Tucker [19]. After that we present the Medvedev-Scanlon classification of periodic subvarieties of $\mathbb{P}_K^n$ under $f \times \ldots \times f$ which plays an important role in the proof of both Theorem 1.1 and Theorem 1.2. In the remaining chapters, we prove the main results of this thesis, propose some related open questions, and briefly describe some work in progress.

We finish this introduction by stating our convention for notation. A function field means a finitely generated field of transcendental degree 1 over a ground field of characteristic 0. Throughout this thesis, $K$ denotes a number field or a function field over the ground field $\kappa$, and $M_K$ denotes the set of places of $K$. In the function field case, by places of $K$, we mean the equivalence classes of the non-trivial valuations on $K$ that are trivial on $\kappa$. We assume that $\kappa$ is relatively algebraically closed in $K$, or equivalently, $\kappa^*$ is exactly the elements of $K^*$ having valuation 0 at every place. This assumption will not affect the generality of our results. For every $v$ in $M_K$, let $K_v$ denote the completion of $K$ with respect to $v$. If $v$ is non-archimedean, we also let $\mathcal{O}_v$ and $k_v$ respectively denote the valuation ring and the residue field of $K_v$. By a variety over $K$, we mean a reduced separated scheme of finite type over $K$. Every Zariski closed subset of a variety is identified with the closed subscheme having the induced reduced closed subscheme structure, and is called a closed subvariety. Curves, surfaces, . . . , and hypersurfaces are not assumed to be irreducible but merely equidimensional. In this thesis, $\mathbb{P}_K^1$ is implicitly equipped with a coordinate function $x$ having only one simple pole and zero which are denoted by $\infty$ and 0 respectively. Every rational $f \in K(X)$ gives a corresponding self-map of $\mathbb{P}_K^1$ by its action on $x$. For every self-map $\mu$ of a set, for every positive integer $n$, we write $\mu^n$ to denote the $n$th iterate of $\mu$, and we define $\mu^0$ to be the identity map. The phrase “for almost all” means “for all but finitely many”.
Chapter 2

Primitive Prime Divisors in Dynamical Sequences

Definition 2.1. Let \( \{a_n\}_{n \geq 1} \) be a sequence of distinct elements in \( K \). A prime \( p \) of \( K \) is said to be a primitive divisor of \( a_N \) if \( v_p(a_N) > 0 \) and \( v_p(a_M) \leq 0 \) for \( 1 \leq M < N \) where \( v_p \) denotes the \( p \)-adic valuation.

The problem of proving the existence of primitive prime divisors is first considered by Bang [3], Zsigmondy [52], and Schinzel [40] in the context of the multiplicative group \( K^* \). Analogous problems in the context of elliptic curves have also been studied (see, for example, [13] and [26]). In this chapter, we are interested in primitive divisors appearing in dynamical sequences which has been studied in [27], [14], [12], [38], [29], and [19]. We first make the following:

Remark 2.2. Let \( \phi(X) \in K(X) \) having degree at least 2. When \( K \) is a function field over the ground field \( \kappa \), we say that \( \phi \) is isotrivial if there exists a fractional linear \( L \in \text{Aut}(\mathbb{P}^1_K) \) such that \( L^{-1} \circ \phi \circ L \in \bar{\kappa}(X) \). Let \( \alpha \in K \). In the number field case, let \( h \) denote the absolute logarithmic Weil height, and let \( \hat{h}_\phi \) denote the corresponding canonical height associated to \( \phi \) (see [42]). In the function field case, let \( h \) denote the Weil height over \( K \), and let \( \hat{h}_\phi \) denote the corresponding canonical height associated to \( \phi \) (see [2]). The condition \( \hat{h}_\phi(\alpha) > 0 \) is equivalent to the condition that \( \alpha \) is \( \phi \)-wandering [42, Chapter 3]. This remains valid in the function field case under the assumption that \( \phi \) is not isotrivial [2]. Finally, if \( L^{-1} \circ \phi \circ L \in \bar{\kappa}(X) \) then the condition \( \hat{h}_\phi(\alpha) > 0 \) is equivalent to the condition that \( L^{-1}(\alpha) \notin \bar{\kappa} \).

Let \( \phi(X) \in K(X) \) having degree at least 2. Let \( \alpha \in K \) such that \( \hat{h}_\phi(\alpha) > 0 \) (see the previous remark), let \( \beta \in K \) such that \( \beta \notin \mathcal{O}_\phi(\alpha) \). We say that \( \beta \) is exceptional if \( \phi^{-2}(\beta) = \{\beta\} \). We have the following conjecture of Ingram-Silverman [27]:

Conjecture 2.3. Let \( \phi(X), \alpha \) and \( \beta \) be as in the last paragraph. We assume that \( \beta \) is not exceptional. Consider the sequence \( \{\phi^n(\alpha) - \beta\}_{n \geq 1} \). Then \( \phi^n(\alpha) - \beta \) has a primitive prime divisor for almost all \( n \).
The following partial result is given by Ingram and Silverman:

**Theorem 2.4** (Ingram-Silverman). *Conjecture 2.3 holds when $\beta$ is $\phi$-preperiodic.*

*Proof.* See [27, p. 292] for the number field case. In the function field case, Ingram and Silverman require that $\phi$ is not isotrivial [27, Remark 4]. However, even when $\phi$ is isotrivial, what is really needed in the proof of their result is that $\hat{h}_\phi(\alpha) > 0$. \hfill $\square$

Before finishing this chapter, we mention another result proving the full Conjecture 2.3 assuming ABC. We refer the readers to [45] or [19] for a statement of the ABC Conjecture over a general number field or function field given by Vojta. In a joint work with Chad Gratton and Thomas Tucker, we prove the following:

**Theorem 2.5.** *Conjecture 2.3 holds when:*

(a) $K$ is a number field satisfying the ABC Conjecture, or

(b) $K$ is a function field.

*Proof.* See [19, Theorem 1.1]. \hfill $\square$

**Remark 2.6.** We can strengthen Theorem 2.5 to prove the existence of “squarefree primitive divisors” (i.e. the value of $v_p$ is 1), see [19, Theorem 1.2]. The proof of Theorem 2.5 in the function field case does not follow verbatim from the proof in the number field case and the “elementary ABC for function fields”. In fact, we use Belyi maps in the number field case. Due to the lack of Belyi maps for function fields, we need a much deeper theorem of Yamanoi [48, Theorem 5] previously conjectured by Vojta [47, p. 71], [46, Conjecture 25.1].

One may view Conjecture 2.3 as a very strong form of the dynamical Hasse principle mentioned in the introduction when $\phi$ is a self-map of $X = \mathbb{P}^1$, and $V$ is the point $\beta$. In the next chapter, we will present the Medvedev-Scanlon description of $f \times \ldots \times f$-periodic subvarieties of $(\mathbb{P}^1)^n$ (where $f(X) \in K[X]$ is a “disintegrated” polynomial of degree at least 2) in a way most suitable for our applications.
Chapter 3

The Medvedev-Scanlon Theorem

Throughout this chapter, let $F$ be an algebraically closed field of characteristic $0$, and $n \geq 2$ a positive integer. We now introduce the notion of disintegrated polynomials. For $d \geq 2$, the Chebyshev polynomial of degree $d$ is the unique polynomial $C_d(X) \in F[X]$ such that $C_d(X + \frac{1}{X}) = X^d + \frac{1}{X^d}$.

Definition 3.1. Let $f(X) \in F[X]$ be a polynomial of degree $d \geq 2$. Then $f$ is said to be special if there is $L \in \text{Aut}(\mathbb{P}^1_F)$ such that $L^{-1} \circ f \circ L$ is either $\pm C_d$ or the power monomial $X^d$. The polynomial $f$ is said to be disintegrated if it is not special.

Here we have adopted the terminology “disintegrated polynomials” used in the Medvedev-Scanlon work [31] which has its origin from model theory. Unfortunately, there is no standard terminology for what we call special polynomials. Complex dynamists describe such maps as having “flat orbifold metric”, Milnor [33] calls them “finite quotients of affine maps”, and Silverman’s book [42] describes them as polynomials “associated to algebraic groups”. The term “special” used here is succinct and sufficient for our purposes. Laura DeMarco also suggests the terminology “exceptional” and “non-exceptional” respectively for “special” and “disintegrated”.

We remark that for every $m > 0$, $f^m$ is disintegrated if and only if $f$ is disintegrated. To prove this, we may assume $F = \mathbb{C}$ by the Lefschetz principle. We then use two well-known results in complex dynamics that $f$ and $f^m$ have the same Julia set, and that a polynomial is disintegrated if and only if its Julia set is not an interval or a circle.

We have the following classification of $f^1 \times \ldots \times f^i$-periodic subvarieties of $(\mathbb{P}^1)^n$ given by Medvedev-Scanlon [31, p. 5] which plays a very important role in the proof of our main results:

Theorem 3.2. Let $f(X) \in F[X]$ be a disintegrated polynomial of degree $d \geq 2$, let $n \geq 2$ and let $\varphi = f^1 \times \ldots \times f : (\mathbb{P}^1_F)^n \longrightarrow (\mathbb{P}^1_F)^n$. Let $V$ be an irreducible $\varphi$-invariant (respectively $\varphi$-periodic) subvariety in $(\mathbb{P}^1_F)^n$. For $1 \leq i \leq n$, let $x_i$ be the chosen coordinate for the $i^{th}$ factor of $(\mathbb{P}^1)^n$. Then $V$ is given by a collection of equations of the following types:
(A) $x_i = \zeta$ where $\zeta$ is a fixed (respectively periodic) point of $f$.

(B) $x_j = g(x_i)$ for some $i \neq j$, where $g(X)$ is a polynomial commuting with $f(X)$ (respectively an iterate of $f(X)$).

We could further describe all the polynomials $g(X)$ in type (B) of Theorem 3.2 as follows.

**Proposition 3.3.** Let $F$ and $f(X)$ be as in Theorem 3.2. We have:

(a) If $g(X) \in F[X]$ has degree at least 2 such that $g$ commutes with an iterate of $f$ then $g$ and $f$ have a common iterate.

(b) Let $M(f^\infty)$ denote the collection of all linear polynomials commuting with an iterate of $f$. Then $M(f^\infty)$ is a finite cyclic group under composition.

(c) Let $\tilde{f} \in F[X]$ be a polynomial of lowest degree at least 2 such that $\tilde{f}$ commutes with an iterate of $f$. Then there exists $D = D_f > 0$ relatively prime to the order of $M(f^\infty)$ such that $\tilde{f} \circ L = LD \circ \tilde{f}$ for every $L \in M(f^\infty)$.

(d) \( \{ \tilde{f}^m \circ L : m \geq 0, L \in M(f^\infty) \} = \{ L \circ \tilde{f}^m : m \geq 0, L \in M(f^\infty) \} \), and these sets describe exactly all polynomials $g$ commuting with an iterate of $f$.

**Proof.** By the Lefschetz principle, we may assume $F = \mathbb{C}$. Part (a) is a well-known result of Ritt [39, p. 399]. For part (b), let $\Sigma_f$ denote the group of linear fractional automorphisms of the Julia set of $f$. It is known that $\Sigma_f$ is finite cyclic [41]. Therefore $M(f^\infty)$, being a subgroup of $\Sigma_f$, is also finite cyclic. By part (a), $f$ and $\tilde{f}$ have the same Julia set. Therefore $\Sigma_f = \Sigma_{\tilde{f}}$.

We now prove part (c). By [41], there exists $D$ such that $\tilde{f} \circ L = LD \circ \tilde{f}$ for every $L \in \Sigma_f = \Sigma_{\tilde{f}}$. To prove that $D$ is relatively prime to the order of $M(f^\infty)$, we let $\tilde{L}$ denote a generator of $M(f^\infty)$, and $N > 0$ such that $\tilde{L} \circ \tilde{f}^N = \tilde{f}^N \circ L$. Hence $\tilde{L} \circ \tilde{f}^N = \tilde{L}^{DN} \circ \tilde{f}^N$. The last equality implies $D^N - 1$ is divisible by the order of $M(f^\infty)$ and we are done.

It remains to show part (d). The given two sets are equal since $D^m$ is relatively prime to the order of $M(f^\infty)$ for every $m \geq 0$. It suffices to show if $g \in F[X]$, $\deg(g) > 1$ and $g$ commutes with $f$ then $g$ has the form $\tilde{f}^m \circ L$. Let $\varphi = f \times f$ be the split self-map of $(\mathbb{P}_F^1)^2$. Now the (possibly reducible) curve $V$ in $(\mathbb{P}_F^1)^2$ given by $\tilde{f}(y) = g(x)$ satisfies $\varphi^M(V) \subseteq V$ for some $M > 0$. Therefore some irreducible component $C$ of $V$ is periodic. By Theorem 3.2, $C$ is given by $y = \psi(x)$ or $x = \psi(y)$ where $\psi$ commutes with an iterate of $f$. Therefore one of the following holds:

(i) $\tilde{f} \circ \psi = g$

(ii) $g \circ \psi = \tilde{f}$
Since $\deg(g) \geq \deg(\tilde{f})$ by the definition of $\tilde{f}$, case (ii) can only happen when $\deg(g) = \deg(\tilde{f})$ and $\psi \in M(f^\infty)$. If this is the case, we can write (ii) into $g = \tilde{f} \circ (\psi)^{-1}$. Thus we can assume (i) always happens. Repeating the argument for the pair $(\tilde{f}, \psi)$ instead of $(\tilde{f}, g)$, we get the desired conclusion. 

\begin{remark}
Proposition 3.3 follows readily from Ritt's theory of polynomial decomposition. The proof given here uses the Medvedev-Scanlon description in Theorem 3.2 and simple results from complex dynamics. In fact, in a joint work in progress with Michael Zieve, we will study and give examples of a lot of rational (and non-polynomial) maps $f(X)$ such that Theorem 3.2 is still valid. Then an analogue of Proposition 3.3, especially part (d), still holds by exactly the same proof.
\end{remark}

We conclude this chapter with a particularly useful property of preperiodic subvarieties of $(\mathbb{P}^1_F)^n$ (under diagonally split disintegrated polynomial maps). Let $f(X)$, $n$ and $\varphi$ be as in Theorem 3.2. Let $V$ be an irreducible $\varphi$-periodic subvariety of $(\mathbb{P}^1_F)^n$. We will associate to $V$ a binary relation $\prec$ on $I = \{1, \ldots, n\}$ as follows. Let $I_V$ denote the set of $1 \leq i \leq n$ such that $V$ is contained in a hypersurface of the form $x_i = \zeta$ where $\zeta$ is a periodic point. The relation $\prec$ is empty if and only if $I_V = I$ (i.e. $V$ is a point). For every $i \in I - I_V$, we include the relation $i \prec j$. For two elements $i \neq j$ in $I - I_V$, we include the relation $i \prec j$ if $V$ is contained in a hypersurface of the form $x_j = g(x_i)$ where $g(X)$ is a polynomial commuting with an iterate of $f(X)$. We have the following properties:

\begin{lemma}
Notations as in the last paragraph. Let $1 \leq i, j, k \leq n$. We have:

(a) Transitivity: if $i \prec j$ and $j \prec k$ then $i \prec k$.

(b) Upper chain extension: if $i \prec j$ and $i \prec k$ then either $j \prec k$ or $k \prec j$.

(c) Lower chain extension: if $i \prec k$ and $j \prec k$ then either $i \prec j$ or $j \prec i$.
\end{lemma}

\begin{proof}
We may assume $i$, $j$, and $k$ are distinct, otherwise there is nothing to prove. Part (a) is immediate from the definition of $\prec$. For part (b), we have that $V$ is contained in hypersurfaces $x_j = g_1(x_i)$ and $x_k = g_2(x_i)$. By Proposition 3.3, we may write $g_1 = g_3 \circ g_2$ or $g_2 = g_3 \circ g_1$ for some $g_3$ commuting with an iterate of $f$. This implies $k \prec j$ or $j \prec k$.

Now we prove part (c). Let $\pi$ denote the projection from $(\mathbb{P}^1_F)^n$ onto the $(i, j, k)$-factor $(\mathbb{P}^1)^3$. We have that $\pi(V)$ is an irreducible $f \times f \times f$-periodic curve of $(\mathbb{P}^1)^3$ contained in the (not necessarily irreducible) curve given by $x_k = g_1(x_i)$ and $x_k = g_2(x_i)$ (note that we must have $\dim(\pi(V)) > 0$ since $i, j, k \notin I_V$). Now we consider the closed embedding:

$$
(\mathbb{P}^1_F)^2 \xrightarrow{\eta} (\mathbb{P}^1_F)^3
$$

defined by $\eta(y_i, y_j) = (y_i, y_j, g_1(y_i))$. Now $\eta^{-1}(\pi(V))$ is an irreducible $f \times f$-periodic curve of $(\mathbb{P}^1_F)^2$ whose projection to each factor $\mathbb{P}_1$ is surjective since $i, j \notin I_V$. Therefore $\eta^{-1}(\pi(V))$ is given by either $y_i = g_3(y_j)$ or $y_j = g_3(y_i)$ for some $g_3$ commuting with an iterate of $f$. This implies either $j \prec i$ or $i \prec j$.
\end{proof}
A chain is either a tuple of one element \((i)\) where \(i \notin I_V\) (equivalently \(i \prec i\)), or an ordered set of distinct elements \(i_1 \prec i_2 \prec \ldots \prec i_l\). If \(\mathcal{I} = (i_1, \ldots, i_l)\) is a chain, we denote the underlying set (or the support) \(\{i_1, \ldots, i_l\}\) by \(s(\mathcal{I})\). Note that it is possible for many chains to have a common support, for example if \(V\) is contained in \(x_j = g(x_i)\) where \(g\) is linear then both \((i, j)\) and \((j, i)\) are chains. By Lemma 3.5, if \(\mathcal{I}\) is a chain, \(i \in I\) and \(i \prec j\) or \(j \prec i\) for some \(j \in \mathcal{I}\) then we can enlarge \(\mathcal{I}\) into a chain whose support is \(s(\mathcal{I}) \cup \{i\}\). We have that there exist maximal chains \(\mathcal{I}_1, \ldots, \mathcal{I}_l\) whose supports partition \(I - I_V\). Although the collection \(\{\mathcal{I}_1, \ldots, \mathcal{I}_l\}\) is not uniquely determined by \(V\), the collection of supports \(\{s(\mathcal{I}_1), \ldots, s(\mathcal{I}_l)\}\) is.

To prove these facts, one may define an equivalence relation \(\sim\) on \(I - I_V\) by \(i \sim j\) if and only if \(i \prec j\) or \(j \prec i\). Then it is easy to prove that \(\{s(\mathcal{I}_1), \ldots, s(\mathcal{I}_l)\}\) is exactly the collection of equivalence classes.

For an ordered subset \(J\) of \(I\), we define the following factor of \((\mathbb{P}^1)^n\):

\[
(\mathbb{P}^1)^J := \prod_{j \in J} \mathbb{P}^1
\]
equipped with the canonical projection \(\pi': (\mathbb{P}^1)^n \to (\mathbb{P}^1)^J\). For a collection of ordered sets \(J_1, \ldots, J_l\) whose underlying (i.e. unordered) sets partition \(I\), we have the canonical isomorphism:

\[
(\mathbb{P}^1)^n \cong (\mathbb{P}^1)^{J_1} \times \ldots \times (\mathbb{P}^1)^{J_l}.
\]

We now have the following result:

**Proposition 3.6.** Let \(f\) and \(\varphi\) be as in Theorem 3.2. Let \(V\) be an irreducible \(\varphi\)-preperiodic subvariety of \((\mathbb{P}^1_F)^n\). Assume that \(\dim(V) > 0\). Let \(I = \{1, \ldots, n\}\), and let \(I_V\) denote the set of all \(i\)'s such that \(V\) is contained in a hypersurface of the form \(x_i = \zeta_i\) where \(\zeta_i\) is \(f\)-preperiodic. We fix a choice of an order on \(I_V\), write \(l = \dim(V)\). There exist a collection of ordered sets \(J_1, \ldots, J_l\) whose underlying sets partition \(I - I_V\) such that under the canonical isomorphism

\[
(\mathbb{P}^1)^n = (\mathbb{P}^1)^{I_V} \times (\mathbb{P}^1)^{J_1} \times \ldots \times (\mathbb{P}^1)^{J_l},
\]

we have:

\[
V = \left(\prod_{i \in I_V} \{\zeta_i\}\right) \times V_1 \times \ldots \times V_l
\]

where \(V_k\) is an \(f \times \ldots \times f\)-preperiodic curve of \((\mathbb{P}^1)^{J_k}\) for \(1 \leq k \leq l\).

**Proof.** Since \(V\) is \(\varphi\)-preperiodic, there exists \(m\) such that \(\varphi^m(V)\) is \(\varphi\)-periodic. The conclusion of the proposition for \(\varphi^m(V)\) will imply the same conclusion for \(V\), hence we may assume \(V\) is \(\varphi\)-periodic. We associate to \(V\) a binary relation \(\prec\) on \(I\) as in the previous paragraphs. Then there exist maximal chains \(\mathcal{I}_1, \ldots, \mathcal{I}_l\) whose supports partition \(I - I_V\). We now take \(J_k = \mathcal{I}_k\) for \(1 \leq k \leq l\). \(\square\)
Chapter 4

The Dynamical Hasse Principle

4.1 Motivation and Main Results

In this chapter, let $S$ be a fixed finite subset of $M_K$ containing all the archimedean places. For every variety $X$ over $K$, we define:

$$X(K,S) = \prod_{v \notin S} X(K_v)$$  \hspace{1cm} (4.1)

equipped with the product topology, where each $X(K_v)$ is given the $v$-adic topology which is Hausdorff by separatedness of $X$. The set $X(K)$ is embedded into $X(K,S)$ diagonally. For every subset $T$ of $X(K,S)$, write $\mathcal{C}(T)$ to denote the closure of $T$ in $X(K,S)$. The following theorem has been established by Poonen and Voloch [36, Theorem A]:

**Theorem 4.1.** Assume that $K$ is a function field. Let $A$ be an abelian variety and $V$ a closed subvariety of $A$ both defined over $K$. Then:

$$V(K) = V(K,S) \cap \mathcal{C}(A(K)).$$  \hspace{1cm} (4.2)

The analogue of Theorem 4.1 when $K$ is a number field is still wide open. The main motivation for Poonen-Voloch theorem is the determination of $V(K)$ especially when $V$ is a curve of genus at least 2 embedded into its Jacobian. More precisely, they are interested in the Brauer-Manin obstruction to the Hasse principle studied by various authors. In fact, the idea of taking the (coarser) intersection between $V(K_p)$ and the $p$-adic closure of $A(K)$ in $A(K_p)$, where $p$ is a prime of $K$, is dated back to Chabauty’s work in the 1940s, and further refined by Coleman in the 1980s. We refer the readers to [36] and the references there for more details.

Now return to our general setting, let $\varphi$ be a $K$-morphism of $X$ to itself, $V$ a closed subvariety of $X$, and $P \in X(K)$ a $K$-rational point of $X$. We have the following inclusion (note the similarity with (4.2) where the group $A(K)$ is replaced by the orbit $O_{\varphi}(P)$):

$$V(K) \cap O_{\varphi}(P) \subseteq V(K,S) \cap \mathcal{C}(O_{\varphi}(P)).$$  \hspace{1cm} (4.3)
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Motivated by the Poonen-Voloch theorem, Hsia and Silverman [25, p. 237–238] ask:

**Question 4.2.** Let \( V^{pp} \) denote the union of all positive dimensional preperiodic subvarieties of \( V \). Assume that \( O_\varphi(P) \cap V^{pp}(K) = \emptyset \). When does equality hold in (4.3)?

The requirement \( O_\varphi(P) \cap V^{pp}(K) = \emptyset \) is necessary as explained in [25, p. 238]. In this thesis, we restrict to the following question:

**Question 4.3.** Assume that \( V \) is preperiodic and \( V(K) \cap O_\varphi(P) = \emptyset \), when can we conclude \( V(K, S) \cap C(O_\varphi(P)) = \emptyset \)?

Our main theorems below will address Question 4.3 when \( X = (\mathbb{P}^1)^n \), and \( \varphi \) is the diagonally split morphism associated to a polynomial \( f(X) \). We begin with the case \( \dim(V) = 0 \):

**Theorem 4.4.** Let \( f(X) \in K[X] \) be a polynomial of degree at least 2, let \( n \geq 2 \) be an integer, and let \( \varphi \) denote the split morphism \( f \times \ldots \times f : (\mathbb{P}^1)_K^n \longrightarrow (\mathbb{P}^1)_K^n \). Let \( V \) be a zero dimensional subvariety of \((\mathbb{P}^1)_K^n\). The following hold:

(a) For every \( P \in (\mathbb{P}^1)_K^n(K) \) such that \( V(K) \cap O_\varphi(P) = \emptyset \), there exist infinitely many primes \( p \) such that \( V(K_p) \) does not intersect the \( p \)-adic closure of \( O_\varphi(P) \).

(b) Question 4.2 has an affirmative answer, namely for every \( P \in X(K) \) we have:

\[
V(K) \cap O_\varphi(P) = V(K, S) \cap C(O_\varphi(P)).
\]

(c) In this part only, we assume \( f \) is special and \( V \) is preperiodic. Then for every \( P \in (\mathbb{P}^1)_K^n(K) \) such that \( V(K) \cap O_\varphi(P) = \emptyset \), for almost all primes \( p \) of \( K \), we have \( V(K_p) \) does not intersect the \( p \)-adic closure of \( O_\varphi(P) \).

Part (b) actually holds for maps of the form \( f_1 \times \ldots \times f_n \) where each \( f_i \) is an arbitrary rational map of degree at least 2. This more general result follows from the main results of Silverman and Voloch [43]. We will see that the trick used to establish part (a) in Section 4.2, which is similar to one used in [43], appears repeatedly in this chapter and can be modified to reduce our problem (when \( \dim(V) > 0 \)) to the étale case (see Section 4.3). Part (c) of Theorem 4.4 could be generalized completely, we have:

**Theorem 4.5.** Let \( f \in K[X] \) be a special polynomial of degree \( d \geq 2 \). Let \( n \geq 2 \), and \( \varphi = f \times \ldots \times f \) be as in Theorem 4.4. Let \( V \) be a subvariety of \((\mathbb{P}^1)_K^n\) such that every irreducible component of \( V_K \) is a preperiodic subvariety. Let \( P \in (\mathbb{P}^1)_K^n(K) \) such that \( V(K) \cap O_\varphi(P) = \emptyset \). Then for almost all primes \( p \) of \( K \), \( V(K_p) \) does not intersect the \( p \)-adic closure of \( O_\varphi(P) \). Consequently, Question 4.3 has an affirmative answer: \( V(K, S) \cap C(O_\varphi(P)) = \emptyset \).

It has been known since the beginning of the theory of complex dynamics that special polynomials and disintegrated polynomials have very different dynamical behaviours. When \( f \) is disintegrated, we are still able to prove that a Hasse principle analogous to Theorem 4.5 holds when \( V \) is a curve or a hypersurface:
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**Theorem 4.6.** Let \( f \in K[X] \) be a disintegrated polynomial of degree \( d \geq 2 \). Let \( n \geq 2 \), and \( \varphi = f \times \ldots \times f \) be as in Theorem 4.4. Let \( V \) be a \( \varphi \)-preperiodic and absolutely irreducible curve or hypersurface of \((\mathbb{P}_K^n)^n\). Let \( P \in (\mathbb{P}_K^n)(K) \) such that \( V(K) \cap \mathcal{O}_\varphi(P) = \emptyset \). Then for infinitely many primes \( p \) of \( K \), the \( p \)-adic closure of \( \mathcal{O}_\varphi(P) \) does not intersect \( V(K_p) \). Consequently, Question 4.3 has an affirmative answer: we have \( V(K, S) \cap \mathcal{C}(\mathcal{O}_\varphi(P)) = \emptyset \).

Although we expect Theorem 4.6 still holds for an arbitrary absolutely irreducible preperiodic subvariety \( V \) (i.e. \( 1 < \dim(V) < n - 1 \)), we need to assume an extra technical assumption, as follows:

**Theorem 4.7.** Let \( f \), \( n \), and \( \varphi \) be as in Theorem 4.6. Assume the technical assumption that every polynomial commuting with an iterate of \( f \) also commutes with \( f \). Let \( V \) be an absolutely irreducible \( \varphi \)-preperiodic subvariety of \((\mathbb{P}_K^n)^n\). Let \( P \in (\mathbb{P}_K^n)(K) \) such that \( V(K) \cap \mathcal{O}_\varphi(P) = \emptyset \). Then there exist infinitely many primes \( p \) of \( K \) such that the \( p \)-adic closure of \( \mathcal{O}_\varphi(P) \) does not intersect \( V(K_p) \). Consequently, Question 4.3 has an affirmative answer: \( V(K, S) \cap \mathcal{C}(\mathcal{O}_\varphi(P)) = \emptyset \).

**Remark 4.8.** The above technical assumption holds for a generic \( f \). In fact, let \( M(f^\infty) \) denote the group of linear polynomials commuting with an iterate of \( f \). By Proposition 3.3, if \( M(f^\infty) \) is trivial then the technical assumption in Theorem 4.7 holds. When \( f \) has degree 2 and is not conjugate to \( X^2 \), we have that \( M(f^\infty) \) is trivial. When \( f \) has degree at least 3, after making a linear change, we can assume:

\[
f(x) = X^d + a_{d-2}X^{d-2} + a_{d-3}X^{d-3} + \ldots + a_0.
\]

It is easy to prove that when \( a_{d-2}a_{d-3} \neq 0 \), the group \( M(f^\infty) \) is trivial.

In the next section, we will give all the preliminary results needed for the proofs of the above Theorems as well as a proof of Theorem 4.4.

### 4.2 An Assortment of Preliminary Results

Our first lemma shows that in order to prove Theorems 4.4–4.7, we are free to replace \( K \) by a finite extension.

**Lemma 4.9.** Let \( L \) be a finite extension of \( K \), \( X \) a variety over \( K \), \( \varphi \) a \( K \)-endomorphism of \( X \), \( V \) a closed subvariety of \( X \) over \( K \), and \( P \) an element of \( X(K) \). Let \( p \) be a prime of \( K \) and \( q \) a prime of \( L \) lying above \( p \). If \( V(L_q) \) does not intersect the \( q \)-adic closure of \( \mathcal{O}_\varphi(P) \) in \( X(L_q) \) then \( V(K_p) \) does not intersect the \( p \)-adic closure of \( \mathcal{O}_\varphi(P) \) in \( X(K_p) \).

**Proof.** Clear. \( \square \)

Before stating the next result, we need some terminology. Let \( p \) be a prime of \( K \), \( \mathcal{X} \) a separated scheme of finite type over \( \mathcal{O}_p \). By the valuative criterion of separatedness [23,
p. 97], we could view \( X(O_p) \) as a subset of \( X(K_p) \), then the \( p \)-adic topology on \( X(O_p) \) is the same as the subspace topology induced by the \( p \)-adic topology on \( X(K_p) \). Every point \( P \in X(O_p) \) is an \( O_p \)-morphism \( \text{Spec}(O_p) \to X \). By the generic point and closed point of \( P \), we mean the image of the generic point and closed point of \( \text{Spec}(O_p) \), respectively. We write \( \bar{P} \) to denote its closed point, which is also identified to the corresponding element in \( X(k_p) \).

The scheme \( X \) is said to be smooth at \( P \) if the structural morphism \( X \to \text{Spec}(O_p) \) is smooth at \( \bar{P} \). Similarly, an endomorphism \( \varphi \) of \( X \) over \( O_p \) is said to be \( \acute{e} \text{tale} \) at \( P \) if it is \( \acute{e} \text{tale} \) at \( \bar{P} \). The following is essentially a main result of [1, Theorem 4.4]:

**Theorem 4.10.** Let \( K, p, X, \) and \( P \in X(O_p) \) be as in the last paragraph. Let \( \varphi \) be an endomorphism of \( X \) over \( O_p \). Assume that \( X \) is smooth and \( \varphi \) is \( \acute{e} \text{tale} \) at every point in the orbit \( O_p(P) \). Let \( V \) be a reduced closed subscheme of \( X \). Assume one of the following sets of conditions:

(a) There exists \( M > 0 \) satisfying \( \varphi^M(V) \subseteq V \). When \( K \) is a function field, we assume that \( P \) is \( \varphi \)-preperiodic modulo \( p \).

(b) \( V \) is a finite set of preperiodic points of \( X(O_p) \).

We have: if \( V(O_p) \) does not intersect \( O_{\varphi}(P) \) then it does not intersect the \( p \)-adic closure of \( O_{\varphi}(P) \).

**Proof.** First assume the conditions in (a). Although the statement in [1, Theorem 4.4] includes smoothness of \( X \) and \( \acute{e} \text{tale} \)ness of \( \varphi \) everywhere, its proof could actually be carried verbatim here.

Now assume the conditions in (b). Define:

\[
\mathcal{V}_1 = \bigcup_{i=0}^{\infty} \varphi^i(V).
\]

Then \( \mathcal{V}_1 \) is a finite set of points in \( X(O_p) \) satisfying \( \varphi(\mathcal{V}_1) \subseteq \mathcal{V}_1 \). If the orbit of \( P \) intersects \( \mathcal{V}_1(O_p) \) then \( P \) is preperiodic and there is nothing to prove. So we may assume otherwise. After reducing mod \( p \), if the orbit of \( P \) does not intersect \( \mathcal{V}_1 \) then there is nothing to prove. So we may assume otherwise, and this assumption gives that \( P \) is preperiodic mod \( p \). All the conditions in part (a) are now satisfied, and we can get the desired conclusion. \( \square \)

**Remark 4.11.** In [1], there are two proofs for part (a) of Theorem 4.10. One proof uses elementary commutative algebra and some intuition on \( p \)-adic distance, while the other one uses the \( p \)-adic uniformization theorem of Bell-Ghioca-Tucker [5].

We remind the readers that if \( K \) is a function field over the constant field \( \kappa \), a rational function \( f \in K(X) \) is said to be isotrivial if there exists a fractional linear map \( L \in \text{Aut}(\mathbb{P}^1_K) \) such that \( L^{-1} \circ f \circ L \in \bar{\kappa}(X) \). The Silverman-Voloch trick mentioned right after Theorem 4.4 is the following (see Section 2 for all the terminology):
Lemma 4.12. Let \( f \in K[X] \) be a polynomial of degree at least 2, and let \( \alpha \in K \) such that \( \hat{h}_f(\alpha) > 0 \) (see Remark 2.2). Let \( \gamma \in K \) be a periodic point of \( f \) such that \( \gamma \) is not an exceptional point of \( f \). Then there are infinitely many primes \( p \) of \( K \) such that \( v_p(f^\mu(\alpha) - \gamma) > 0 \) for some \( \mu \) depending on \( p \).

Proof. This follows from the deeper result of Ingram-Silverman (Theorem 2.4) that almost all elements of the sequence \((f^\mu(\alpha) - \gamma)\) have a primitive divisor. 

Remark 4.13. If the exact \( f \)-period of \( \gamma \) is greater than 2 then \( \gamma \) is not an exceptional point of \( f \) [27, Remark 6].

Remark 4.14. We could actually prove Lemma 4.12 without using the Ingram-Silverman theorem as follows. Define \( \ell(X) = \frac{1}{X-\gamma} \), and let \( w = \ell \circ f \circ \ell^{-1} \) be the conjugate of \( f \) by \( \ell \). Note that \( w^n(\ell(\alpha)) = \frac{1}{f^n(\alpha) - \gamma} \). Lemma 4.12 follows from the finiteness of integral elements in the \( w \)-orbit of \( \ell(\alpha) \) [44, Theorem B]. The reason we give the above proof using primitive prime divisors is because this is the trick used by Silverman-Voloch to prove a more general dynamical Brauer-Manin obstruction for a more general rational map. It is also used in a recent paper of Faber-Granville [14] on “doubly primitive divisors”.

We can use Lemma 4.12 to prove the following:

Lemma 4.15. Let \( f \) be as in Lemma 4.12. Let \( \alpha \) be an element of \( \mathbb{P}^1(K) \) and \( V \) a finite subset of \( \mathbb{P}^1(K) \) such that the orbit of \( \alpha \) does not intersect \( V \). Then there are infinitely many primes \( p \) such that the \( p \)-adic closure of the orbit of \( \alpha \) does not intersect \( V \).

Proof. If \( \alpha \) is preperiodic, there is nothing to prove. We assume that \( \alpha \) is wandering. If \( \hat{h}_f(\alpha) = 0 \), we must have that \( K \) is a function field and \( f \) is isotrivial [6]. After replacing \( K \) by a finite extension, and making a linear change, we may assume that \( f \in \kappa[X] \) and \( \alpha \in \kappa \). Now the conclusion of the lemma is obvious since the orbit of \( \alpha \) is discrete in the \( p \)-adic topology for every \( p \).

What remains now is the case \( \hat{h}_f(\alpha) > 0 \). For almost all \( p \), we have \( v_p(\alpha) \geq 0 \) and \( f \in \mathcal{O}_p[X] \), so \( v_p(f^m(\alpha)) \geq 0 \) for all \( m \). Therefore we can assume \( \infty \notin V \). Let \( u_1, \ldots, u_q \) be all elements of \( V \). By Lemma 4.9, we can assume there is a periodic point \( \gamma \in K \) of exact period at least 3 and the orbit of \( \gamma \) does not contain \( u_i \) for \( 1 \leq i \leq q \). Hence there is a finite set of primes \( T \) such that:

\[
\begin{align*}
f \in \mathcal{O}_p[X] \text{ and } v_p(u_i - f^m(\gamma)) &= 0 \quad \forall m \geq 0 \quad \forall 1 \leq i \leq q \quad \forall p \notin T. 
\end{align*}
\]

(4.4)

Now by Lemma 4.12, there are infinitely many primes \( p \notin T \) such that:

\[
v_p(f^\mu(\alpha) - \gamma) > 0 \text{ for some } \mu = \mu_p
\]

(4.5)

Fix any \( p \notin T \) that gives (4.5), write \( \mu = \mu_p \). Thus \( v_p(f^m(\alpha) - f^{m-\mu}(\gamma)) > 0 \) for every \( m \geq \mu \). Together with (4.4), we have \( v_p(f^m(\alpha) - u_i) = 0 \) for every \( m \geq \mu \) and \( 1 \leq i \leq q \). This implies that \( V \) does not intersect the \( p \)-adic closure of the \( f \)-orbit of \( \alpha \).
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Now we have all the results needed to prove Theorem 4.4:

Proof of Theorem 4.4: By Lemma 4.9, we can replace $K$ by a finite extension so that $V$ is a finite set of points in $(\mathbb{P}^1)^n(K)$.

For part (a), note that if $P$ is $\varphi$-preperiodic then there is nothing to prove, hence we can assume $P$ is wandering. Write $P = (a_1, \ldots, a_n)$, without loss of generality, we assume $a_1$ is wandering with respect to $f$. Let $U$ denote the finite subset of $\mathbb{P}^1(K)$ consisting of the first coordinates of points in $V$. There is the largest $N$ such that $f^N(a_1) \in U$. We simply replace $P$ by $\varphi^{N+1}(P)$ and assume the $f$-orbit of $a_1$ does not contain any element of $U$. Then our conclusion follows from Lemma 4.15.

Part (b) follows easily from part (a). As before, we can assume $P$ is not preperiodic, hence there is the largest $N$ such that $\varphi^N(P) \in V(K)$. Replacing $P$ by $\varphi^{N+1}(P)$, we can assume that $V(K) \cap \mathcal{O}_\varphi(P) = \emptyset$, then part (a) implies

$$V(K, S) \cap C(\mathcal{O}_\varphi(P)) = \emptyset = V(K) \cap \mathcal{O}_\varphi(P).$$

For part (c), we first consider the case $L \circ f \circ L^{-1} = X^d$ for some linear polynomial $L \in K[X]$. By extending $K$, we may assume $L \in K[X]$. Since $L$ yields a homeomorphism from $\mathbb{P}^1(K_p)$ to itself for almost all $p$, we may assume $f(X) = X^d$. As before, we can assume the first coordinate $a_1$ of $P$ is wandering. Since $U$ contains only $f$-preperiodic points (by preperiodicity of $V$), the $f$-orbit of $a_1$ does not contain any element of $U$. For almost all $p$, the first coordinates of points in the $\varphi$-orbit of $P$ is a $p$-adic unit. Therefore we can exclude from $V$ all the points having first coordinates 0 or $\infty$, hence $U \subseteq \mathbb{G}_m(K)$. Let $p$ be a prime not dividing $d$ such that $a_1$ and all elements of $U$ are $p$-adic units. We now apply Theorem 4.10 for $\mathcal{X} = \mathbb{G}_m$ over $\mathcal{O}_p$, $\mathcal{Y} = U \subseteq \mathbb{G}_m(\mathcal{O}_p)$, the self-map being the $d^{th}$-power map, and the orbit of $a_1$. Since the $p$-adic closure of the orbit of $a_1$ does not intersect $U(K_p)$, the $p$-adic closure of $P$ does not intersect $V(K_p)$.

For the case $L \circ f \circ L^{-1} = \pm C_d(X)$, we use the self-map of $(\mathbb{P}^1)^n$ given by:

$$(x_1, \ldots, x_n) \mapsto (x_1 + \frac{1}{x_1}, \ldots, x_n + \frac{1}{x_n})$$

to reduce to the case that $f$ is conjugate to $\pm X^d$ which has just been treated. This finishes the proof of Theorem 4.4.

For the rest of this section, we assume that $f \in K[X]$ is a disintegrated polynomial of degree $d \geq 2$, $n \geq 2$, and $\varphi = f \times \ldots \times f$ be the corresponding self-map of $(\mathbb{P}^1)^n$. Let $V$ be a $\varphi$-preperiodic and absolutely irreducible subvariety of $(\mathbb{P}^1)^n$. Let $I = \{1, \ldots, n\}$, and let $I_V$ be as in Proposition 3.6. Let $\pi_1$ and $\pi_2$ denote the projection from $(\mathbb{P}^1)^n_K$ onto $(\mathbb{P}^1)^I$ and $(\mathbb{P}^1)^{I-I}$, respectively. Let $\varphi_1$ and $\varphi_2$ respectively denote the diagonally split self-map of $(\mathbb{P}^1)^I$ and $(\mathbb{P}^1)^{I-I}$ associated to $f$. We have that $Z := \pi_1(V)$ is a $\varphi_1$-preperiodic point of $(\mathbb{P}^1)^I$, and $W := \pi_2(V)$ is a $\varphi_2$-preperiodic subvariety of $(\mathbb{P}^1)^{I-I}$. By Proposition 3.6, we have that $V = Z \times W$ under the canonical identification $(\mathbb{P}^1)^n = (\mathbb{P}^1)^I \times (\mathbb{P}^1)^{I-I}$. We will use the following lemma in the proofs of Theorem 4.6 and Theorem 4.7:
Lemma 4.16. Assume that $W$ satisfies the following property. For every point $P_2 \in (\mathbb{P}^1)^{I-I_V}(K)$ such that the orbit $\mathcal{O}_{\varphi_2}(P_2)$ does not intersect $W(K)$, there exist infinitely many primes $p$ such that the $p$-adic closure of $\mathcal{O}_{\varphi_2}(P_2)$ does not intersect $W(K_p)$.

Then for every point $P \in (\mathbb{P}^1)^n(K)$ such that the orbit $\mathcal{O}_\varphi(P)$ does not intersect $W(K)$, there exist infinitely many primes $p$ such that the $p$-adic closure of $\mathcal{O}_\varphi(P)$ does not intersect $V(K_p)$.

Proof. Assume there is the largest $N$ such that $\varphi^N(\pi_1(P)) = Z$. Replace $P$ by $\varphi^{N+1}(P)$, we can assume that the $\varphi$-orbit of $\pi_1(P)$ does not contain $Z$. By Theorem 4.4, there exist infinitely many primes $p$ such that the $p$-adic closure $C_p$ of $\mathcal{O}_{\varphi_2}(\pi_1(P))$ does not contain $Z$. For each such $p$, the $p$-adic closure of $\mathcal{O}_\varphi(P)$ is contained in $C_p \times (\mathbb{P}^1)^{I-I_V}(K_p)$ which is disjoint from $V(K_p)$.

Now assume $\varphi^n(\pi_1(P)) = Z$ for infinitely many $n$. This implies that $Z$ is periodic and $\pi_1(P)$ is preperiodic. Replacing $P$ by an iterate, we may assume $\pi_1(P) = Z$. Let $N$ denote the exact period of $Z$. Since $\mathcal{O}_\varphi(P)$ does not intersect $V$, we have that $\mathcal{O}_{\varphi_2}(\pi_2(P))$ does not intersect $W$. By the assumption on $W$, there exist infinitely many primes $p$ such that the $p$-adic closure $C_p$ of $\mathcal{O}_{\varphi_2}(\pi_2(P))$ does not intersect $W(K_p)$. For each such $p$, the $p$-adic closure of $\mathcal{O}_\varphi(P)$ is contained in:

$$\left( \bigcup_{i=1}^{N-1} \{ \varphi_1(Z) \} \times (\mathbb{P}^1)^{I-I_V}(K_p) \right) \cup \{ Z \} \times C_p$$

which is disjoint from $V(K_p)$. \qed

4.3 Proof of Theorem 4.6

Let $f \in K[X]$ be a disintegrated polynomial of degree $d \geq 2$. By Theorem 3.2, for every preperiodic hypersurface $H$ of $(\mathbb{P}^1)^n(K)$, there exist $1 \leq i < j \leq n$ such that $H = \pi^{-1}(C)$ where $\pi$ denotes the projection onto the $(i,j)$-factor and $C$ is an $f \times f$-preperiodic curve of $(\mathbb{P}^1)^2$. Therefore it suffices to prove Theorem 4.6 when $V$ is a curve.

Let $\varphi$, $V$ and $P \in (\mathbb{P}^1)^n(K)$ such that $V(K) \cap \mathcal{O}_{\varphi}(P) = \emptyset$ and $\dim(V) = 1$ as in Theorem 4.6 and the discussion in the last paragraph. Let $I$ and $I_V$ be as in Proposition 3.6. Let $\hat{f}$, $M(f^\infty)$, and $D = D_f$ be as in Proposition 3.3. Now we prove that there are infinitely many primes $p$ of $K$ such that $V(K_p)$ does not intersect the $p$-adic closure of $\mathcal{O}_\varphi(P)$. By Lemma 4.9, we can assume $\hat{f}$ and all elements in $M(f^\infty)$ have coefficients in $K$.

Step 1: We first consider the case $V$ is periodic.

By Lemma 4.16, we may assume that $I_V = \emptyset$. By Theorem 3.2, Proposition 3.6 and the discussion before it, we can relabel the factors of $(\mathbb{P}^1)^n$ and rename the coordinate functions of all the factors as $x$, $y_1, \ldots, y_{n-1}$ such that $V$ is given by the equations: $y_i = g_i(x)$ for $1 \leq i \leq n-1$, where $g_i$ commutes with an iterate of $f$ for $1 \leq i \leq n-1$ and $\deg(g_1) \leq \ldots \leq \deg(g_{n-1})$. Write $P = (a, b_1, \ldots, b_{n-1})$. 

\begin{itemize}
  \item \textbf{Step 1:} We first consider the case $V$ is periodic.
  \item By Lemma 4.16, we may assume that $I_V = \emptyset$. By Theorem 3.2, Proposition 3.6 and the discussion before it, we can relabel the factors of $(\mathbb{P}^1)^n$ and rename the coordinate functions of all the factors as $x$, $y_1, \ldots, y_{n-1}$ such that $V$ is given by the equations: $y_i = g_i(x)$ for $1 \leq i \leq n-1$, where $g_i$ commutes with an iterate of $f$ for $1 \leq i \leq n-1$ and $\deg(g_1) \leq \ldots \leq \deg(g_{n-1})$. Write $P = (a, b_1, \ldots, b_{n-1})$. 
\end{itemize}
Step 1.1: we consider the easy case that \( a \) is \( f \)-preperiodic. Replacing \( P \) by an iterate, we can assume that \( a \) is \( f \)-periodic of exact period \( N \). The \( \varphi \)-orbit of \( P \) is:

\[
\{(f^i(a), f^{i+N}(b_1), \ldots, f^{i+N}(b_{n-1})) : t \geq 0, \ 0 \leq i < N\}.
\]

Since this orbit does not intersect \( V(K) \), we have

\[
\forall t \geq 0 \ \forall 0 \leq i < N \ \exists 1 \leq j \leq n - 1 \ (f^{i+N}(b_j) \neq g_j(f^i(a))). \tag{4.6}
\]

For each \( 0 \leq i < N \) and \( 1 \leq j \leq n - 1 \), denote \( B_{i,j} = (f^i)^{-1}(\{g_j(f^i(a))\}) \). Denote

\[
B = \bigcup_{0 \leq i < N} B_{i,1} \times \ldots \times B_{i,n-1}
\]

which is a finite set of (preperiodic) points of \((\mathbb{P}^1)^{n-1} \). Let \( b = (b_1, \ldots, b_{n-1}) \) and let \( \phi \) denote the self-map \( f \times \ldots \times f \) of \((\mathbb{P}^1)^{n-1} \). By (4.6), we have \( \phi^{iN}(b) \notin B \) for every \( t \geq 0 \). By Theorem 4.4, there exist infinitely many primes \( p \) such that the \( p \)-adic closure \( C_p \) of \( \{\phi^{iN}(b) : t \geq 0\} \) does not intersect \( B \). For each such \( p \), the \( p \)-adic closure of the orbit of \( P \) lies in:

\[
\bigcup_{0 \leq i < N} \{f^i(a)\} \times \phi^i(C_p)
\]

which is disjoint from \( V(K_p) \).

Step 1.2: we consider the case \( a \) is \( f \)-wandering and \( h_f(a) = 0 \). Hence \( K \) is a function field and \( f \) is isotrivial by [6]. After replacing \( K \) by a finite extension, and making a linear change, we may assume that \( f \in \kappa[X] \) and \( a \in \kappa \). If \( h_f(b_i) = 0 \) for every \( 1 \leq i \leq n - 1 \), then \( b_i \in \kappa \) for every \( 1 \leq i \leq n - 1 \). Then the orbit \( O_{\varphi}(P) \) is discrete in the \( p \)-adic topology for every \( p \), and the conclusion of the theorem is obvious. Hence we assume that there is \( 1 \leq j \leq n - 1 \) such that \( h_f(b_j) > 0 \). Replacing \( K \) by a finite extension if necessary, we assume that there is an \( f \)-periodic \( \gamma \in \kappa \) of exact period at least 3. By Lemma 4.12, there is an infinite set of primes \( T \) such that for every \( p \in T \):

\[
v_p(f^\mu(b_j) - \gamma) > 0 \text{ for some } \mu = \mu_p. \tag{4.7}
\]

For each \( p \in T \), if the \( p \)-adic closure of \( O_{\varphi}(P) \) intersects \( V(K_p) \) then we must have:

\[
v_p(f^l(b_j) - g_j(f^l(a))) > 0 \text{ for some } l = l_p \geq \mu_p. \tag{4.8}
\]

From (4.7) and (4.8), we have:

\[
v_p(f^{l-\mu}(\gamma) - g_j(f^l(a))) > 0.
\]

Since \( a, \gamma \in \kappa \) and \( f \in \kappa[X] \), this equality means \( f^{l-\mu}(\gamma) = g_j(f^l(a)) \). Hence \( a \) is \( f \)-preperiodic, contradiction. Therefore, for every \( p \in T \), the \( p \)-adic closure of \( O_{\varphi}(P) \) does not intersect \( V(K_p) \).
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**Step 1.3:** we turn to the most difficult case, namely \( \hat{h}_f(a) > 0 \). For each \( 1 \leq j \leq n - 1 \), write \( g_j = L_j \circ f^{m_j} \).

For almost all \( p \), we have \( v_p(f^n(a)) \geq 0 \) for every \( n \geq 0 \). If for some \( 1 \leq j \leq n - 1 \), \( b_j = \infty \) then for almost all \( p \), the \( p \)-adic closure of the orbit of \( P \) lies in:

\[
\{(x, y_1, \ldots, y_{j-1}, \infty, y_{j+1}, \ldots, y_{n-1}) : x \in K_p, \, v_p(x) \geq 0\}
\]

which is disjoint from \( V(K_p) \). So we can assume \( b_j \neq \infty \) for every \( 1 \leq j \leq n - 1 \).

By taking a finite extension of \( K \) if necessary, we choose an \( f \)-periodic point \( \gamma \in K \) of exact period \( N \geq 3 \) such that every point of the form \( L \circ f^k(\gamma) \), where \( L \in M(f^{\infty}) \) and \( k \geq 0 \), is not a zero of the derivative \( \tilde{f}'(X) \) of \( \tilde{f}(X) \). Equivalently, we require that the \( f \)-orbit of \( \gamma \) does not contain any element of the form \( L^{-1}(\delta) \) where \( L \in M(f^{\infty}) \) and \( \delta \) is a root of \( \tilde{f}'(X) \). We briefly explain why this is possible. By Proposition 3.3 \( M(f^{\infty}) \) is finite, and \( \gamma \) is \( \tilde{f} \)-periodic since \( \tilde{f} \) and \( f \) have a common iterate. So we can simply require that the \( \tilde{f} \)-period of \( \gamma \) is sufficiently large.

By Lemma 4.12, there is an infinite set of primes \( R \) such that for every \( p \in R \), all of the following hold:

\[
a, b_1, \ldots, b_{n-1} \in \mathcal{O}_p, \text{ in other words } P \in \mathbb{A}^n(\mathcal{O}_p)
\]

\[
v_p(\tilde{f}'(\tilde{f}^l \circ f^k(\gamma))) = 0 \quad \forall l, k \geq 0
\]

\[
\tilde{f}, f \text{ and elements of } M(f^{\infty}) \text{ are in } \mathcal{O}_p[X] \text{ with } p \text{-adic units leading coefficients}
\]

\[
v_p(\tilde{f}^\mu(a) - \gamma) > 0 \text{ for some } \mu = \mu_p.
\]

Note that (4.10) is possible since there are only finitely many elements of the form \( \tilde{f}^l \circ f^k(\gamma) \), and these elements are not a root of \( \tilde{f}' \) by the choice of \( \gamma \) (and Proposition 3.3).

Now fix a prime \( p \) in \( R \) and write \( \mu = \mu_p \), we still use \( V \) to denote the model \( y_j = L_j \circ f^{m_j}(x) \) over \( \mathcal{O}_p \), hence it makes sense to write \( V(\mathcal{O}_p) \) and \( V(k_p) \). We also use \( P \), and \( \varphi \) to denote the corresponding models over \( \mathcal{O}_p \). Replacing \( P \) by \( \varphi^\mu(P) \), we can assume that \( v_p(a - \gamma) > 0 \). This gives that \( a \) is \( f \)-periodic modulo \( p \) and:

\[
v_p(\tilde{f} \circ f^k(a) - \tilde{f}' \circ f^k(\gamma)) > 0 \quad \text{and} \quad v_p(\tilde{f}'(\tilde{f}^l \circ f^k(a)) - \tilde{f}'(\tilde{f}^l \circ f^k(\gamma))) > 0 \quad \forall l, k \geq 0
\]

The second inequality in (4.13) together with (4.10) give:

\[
v_p(\tilde{f}'(\tilde{f}^l \circ f^k(a))) = 0 \quad \forall l, k \geq 0
\]

By (4.14) and induction, we have:

\[
v_p((\tilde{f}^m)'(\tilde{f}^l \circ f^k(a))) = 0 \quad \forall m, l, k \geq 0
\]

By Proposition 3.3 and condition (4.11), the derivative of an iterate of \( f \) has the form \( u f^m \) for some \( m \geq 0 \), and some \( p \)-adic unit \( u \). Therefore identity (4.15) (with \( l = 0 \)) implies:

\[
v_p((f^m)'(f^k(a))) = 0 \quad \forall m, k \geq 0
\]
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Since the \( \varphi \)-orbit of \( P \) lies in \( A^n(\mathcal{O}_p) \) which is closed in \((\mathbb{P}^1)^n(K_p)\), it suffices to show that \( V(\mathcal{O}_p) \) does not intersect the \( p \)-adic closure of the \( \varphi \)-orbit of \( P \). Assume there is \( \eta \) such that the \( \text{mod } p \) reduction \( \varphi^n(\bar{P}) \) lies in \( V(k_p) \), otherwise there is nothing to prove. After replacing \( P \) by \( \varphi^n(P) \), we can assume \( \eta = 0 \), or in other words \( \bar{P} \in V(k_p) \). This means
\[
v_p(b_j - L_j \circ \tilde{f}^{m_j}(a)) > 0 \quad \forall 1 \leq j \leq n-1.
\]
(4.17)

Note that \( L_j \circ \tilde{f}^{m_j} \) commutes with an iterate of \( f \), therefore (4.17) together with the \( f \)-periodicity mod \( p \) of \( a \) give that \( b_j \) is \( f \)-preperiodic mod \( p \) for \( 1 \leq j \leq n-1 \). Therefore \( P \) is \( \varphi \)-preperiodic mod \( p \).

Inequality (4.17) shows that:
\[
v_p(\tilde{f}^l \circ f^k(b_j) - \tilde{f}^l \circ f^k \circ L_j \circ \tilde{f}^{m_j}(a)) > 0 \quad \forall l, k \geq 0 \quad \forall 1 \leq j \leq n-1.
\]
(4.18)

Our next step is to show:
\[
v_p(\tilde{f}^l \circ f^k \circ L_j \circ \tilde{f}^{m_j}(a)) = 0 \quad \forall l, k \geq 0 \quad \forall 1 \leq j \leq n-1
\]
(4.19)

By Proposition 3.3, write \( \tilde{f}^l \circ f^k \circ L_j \circ \tilde{f}^{m_j} = L \circ \tilde{f}^A \) where \( L \in M(f^\infty) \) and \( A \geq 0 \) depending on \( k, l, m_j \). Let \( c \) denote the leading coefficient of \( L \), by Proposition 3.3 we have:
\[
(\tilde{f} \circ L \circ \tilde{f}^A)'(a) = (L^D \circ \tilde{f}^{A+1})'(a) = c^D(\tilde{f}^{A+1})'(a)
\]
(4.20)

and
\[
(\tilde{f} \circ L \circ \tilde{f}^A)'(a) = \tilde{f}'(L \circ \tilde{f}^A(a))c(\tilde{f}^A)'(a)
\]
(4.21)

Since \( c \) is a \( p \)-adic unit, (4.20) and (4.21) imply:
\[
v_p((\tilde{f}^{A+1})'(a)) = v_p(\tilde{f}'(L \circ \tilde{f}^A(a))(\tilde{f}^A)'(a))
\]
(4.22)

Now (4.19) follows from (4.15), and (4.22).

By (4.18) and (4.19), we have:
\[
v_p((\tilde{f}^l \circ f^k(b_j)) = 0 \quad \forall l, k \geq 0 \quad \forall 1 \leq j \leq n-1
\]
(4.23)

By (4.23) and induction, we have:
\[
v_p((\tilde{f}^m)'(f^k(b_j))) = 0 \quad \forall m, k \geq 0 \quad \forall 1 \leq j \leq n-1
\]
(4.24)

By Proposition 3.3 and condition (4.11), the derivative of an iterate of \( f \) has the form \( u(\tilde{f}^m)' \) for some \( m \geq 0 \), and some \( p \)-adic unit \( u \). Identity (4.24) (with \( l = 0 \)) implies:
\[
v_p((f^m)'(f^k(b_j))) = 0 \quad \forall m, k \geq 0 \quad \forall 1 \leq j \leq n-1
\]
(4.25)

Now (4.16) and (4.25) show that the \( \mathcal{O}_p \)-morphism \( \varphi \) is étale at every \( \mathcal{O}_p \)-valued point in the orbit of \( P \). Together with the fact that \( P \) is preperiodic mod \( p \), we can apply Theorem 4.10 to get the desired conclusion. This finishes the case \( V \) is periodic and \( I_V = \emptyset \).
Step 2: assume $V$ is preperiodic and not periodic, hence there exist $k > 0$ and $M > 0$ such that $\varphi^{k+M}(V) = \varphi^k(V)$. For $0 \leq i < M$, write $V_i = \varphi^{k+i}(V)$. Then we have that $V_i$ is periodic for every $0 \leq i < M$.

By Lemma 4.16, we may assume $I_V = \emptyset$. As in Step 1, we can relabel the factors of $(\mathbb{P}^1)^n$ and rename the coordinate functions into $x, y_1, \ldots, y_{n-1}$ so that for each $0 \leq i < M$, the periodic curve $V_i$ is given by equations $y_j = g_{i,j}(x)$ for $1 \leq j \leq n-1$, where $g_{i,j}$ commutes with an iterate of $f$ and $\deg(g_{i,1}) \leq \ldots \leq \deg(g_{i,n-1})$.

Since $V$ is not periodic, $V$ and $V_i$ are distinct curves, hence $V \cap V_i$ is a finite set of points for every $0 \leq i < M$. By Lemma 4.9, we extend $K$ such that $\mathbb{P}^1(K)$ contains the coordinates of all these points.

Now we assume that for almost all $p$, the $p$-adic closure of $\mathcal{O}_\varphi(P)$ intersects $V(K_p)$ and we will arrive at a contradiction. Because $V_0 = \varphi^0(V)$, for every such $p$, the $p$-adic closure of $\mathcal{O}_\varphi(P)$ intersects $V_0(K_p)$. Since $V_0$ is periodic, the conclusion of Theorem 4.6 has been established for $V_0$. We must have that $V_0(K)$ contains an element in the orbit of $P$. By ignoring the first finitely many elements in that orbit, we may assume $P \in V_0(K)$. Then we have $\varphi^{i+M}(P) \in V_i(K)$ for all $t \geq 0$, $0 \leq i < M$. Let $a$ denote the $x$-coordinate of $P$. For each $0 \leq i < M$, let $n_i = |V \cap V_i|$, and let $u_{i,1}, \ldots, u_{i,n_i}$ denote the $x$-coordinates of points in $V \cap V_i$. Since $V_i$ is defined by $y_j = g_i(x)$ for $1 \leq j \leq n-1$, every point on $V_i$ is uniquely determined by its $x$-coordinate. Since the orbit of $P$ does not intersect $V(K)$, we have:

$$f^{i+M}(a) \notin \{u_{i,1}, \ldots, u_{i,n_i}\} \forall t \geq 0, \forall 0 \leq i < M.$$

Write $\mathcal{A} = \bigcup_{0 \leq i < M} (f^i)^{-1}(\{u_{i,1}, \ldots, u_{i,n_i}\})$. We have that $f^{i+M}(a) \notin \mathcal{A}$ for all $t \geq 0$. By Theorem 4.4, there exist infinitely many primes $q$ such that the $q$-adic closure $C_q$ of $\{f^{i+M}(a) : t \geq 0\}$ does not intersect $\mathcal{A}$. Now the $q$-adic closure of the orbit of $P$ is contained in:

$$\bigcup_{0 \leq i < M} (V_i(K_q) \cap \{(x, y_1, \ldots, y_{n-1}) \in (\mathbb{P}^1)^n(K_q) : x \in f^i(C_q)\})$$

which is disjoint from $V(K_q)$. This gives a contradiction and finishes the proof of Theorem 4.6.

### 4.4 Proof of Theorem 4.7

In this section, we prove Theorem 4.7 by using induction on $n$. The cases $n \in \{1, 2, 3\}$ or $\dim(V) \in \{0, 1, n-1\}$ have been established by Theorem 4.4 and Theorem 4.6 even without the extra technical assumption of Theorem 4.7. Now assume $N > 3$ and Theorem 4.7 holds for all $1 \leq n < N$, we consider the case $n = N$. We may assume $\dim(V) > 1$. By Lemma 4.16, we may assume $I_V = \emptyset$.

**Step 1:** assume $V$ is periodic. By Theorem 3.2, there exist $1 \leq i < j \leq n$ such that the image $\pi(V)$ of $V$ under the projection

$$\pi : (\mathbb{P}^1)^n \to (\mathbb{P}^1)^2$$
onto the \((i, j)\)-factor is a periodic curve. We may assume \((i, j) = (1, 2)\). If \(\pi(O_\varphi(P))\) does not intersect \(\pi(V)(K)\) then we can apply the induction hypothesis. Otherwise, by ignoring the first finitely many elements in the orbit of \(P\), we may assume \(\pi(P) \in \pi(V)(K)\).

Since \(I_V = \emptyset\), we may assume \(\pi(V)\) is given by the equation \(x_2 = g(x_1)\) where \(g\) commutes with an iterate of \(f\) (the case \(x_1 = g(x_2)\) is similar). Our technical assumption gives that \(g\) commutes with \(f\). We consider the closed embedding:

\[ (\mathbb{P}^1)^{n-1} \overset{e}{\longrightarrow} (\mathbb{P}^1)^n \]
defined by \(e(y_1, \ldots, y_{n-1}) = (y_1, g(y_1), y_2, \ldots, y_{n-1})\). By pulling back under \(e\), we reduce our problem to the subvariety \(e^{-1}(V)\) of \((\mathbb{P}^1)^{n-1}\) and apply the induction hypothesis. This finishes the case \(V \) is periodic.

**Step 2:** assume \(V\) is preperiodic and not periodic. Write \(\delta = \dim(V)\). By Proposition 3.6 and without loss of generality, there exist \(m_0 = 0 < m_1 < m_2 < \ldots < m_\delta = n\) such that \(V = C_1 \times C_2 \times \ldots \times C_\delta\) where each \(C_i\) is an \(f \times \ldots \times f\)-preperiodic curve of \((\mathbb{P}^1)^{m_i-m_{i-1}}\) for \(1 \leq i \leq \delta\). For \(1 \leq i \leq \delta\), let \(\pi_i\) denote the corresponding projection from \((\mathbb{P}^1)^n\) onto \((\mathbb{P}^1)^{m_i-m_{i-1}}\), and let \(\varphi_i\) denote the self-map \(f \times \ldots \times f\) of \((\mathbb{P}^1)^{m_i-m_{i-1}}\). If \(P\) is preperiodic then there is nothing to prove, hence we may assume \(P\) is wandering. Without loss of generality, we assume \(\pi_1(P)\) is \(\varphi_1\)-wandering.

**Step 2.1:** assume \(C_1\) is not \(\varphi\)-periodic (recall that it is preperiodic). Then the set

\[ \bigcup_{j > 0} C_1 \cap \varphi_j^1(C_1) \]
is finite. Since \(\pi_1(P)\) is wandering, there are only finitely many \(j\)'s such that \(\varphi_j^1(\pi_1(P))\) is contained in \(C_1(K)\). Ignore finitely many points in the orbits of \(P\), we may assume that the \(\varphi_1\)-orbit of \(\pi_1(P)\) does not intersect \(C_1(K)\). Then we can apply the induction hypothesis for the data \((\mathbb{P}^1)^{m_1}, \varphi_1, \pi_1(P), C_1\).

**Step 2.2:** assume \(C_1\) is \(\varphi\)-periodic. If the \(\varphi\)-orbit of \(\pi_1(P)\) does not intersect \(C_1(K)\) then we can apply the induction hypothesis as above. So we may assume some element in this orbit is in \(C_1(K)\). Replacing \(P\) by an iterate, we may assume \(\pi_1(P) \in C_1(K)\). Since \(I_V = \emptyset\), the curve \(C_1\) is not contained in any hypersurface of the form \(x_j = \gamma\). By Proposition 3.6 and the discussion before it, we know that \(C_1\) is either \(\mathbb{P}^1\) if \(m_1 = 1\) or is given by equations of the form (after possibly relabeling the variables \(x_1, \ldots, x_{m_1}\)): \(x_2 = g_1(x_1), x_3 = g_2(x_1), \ldots, x_{m_1} = g_{m_1-1}(x_{m_1-1})\), where each \(g_j\) commutes with an iterate of \(f\). By our technical assumption, every \(g_j\) commutes with \(f\). Hence \(C_1\) is \(\varphi_1\)-invariant, and we have \(\pi_1(\varphi^l(P)) \in C_1(K)\) for every \(l \geq 0\). Let \(P'\) denote the image of \(P\) under the projection from \((\mathbb{P}^1)^n\) to \((\mathbb{P}^1)^{m_2-m_1} \times \ldots \times (\mathbb{P}^1)^{m_\delta-m_\delta-1}\). We now apply the induction hypothesis for the data:

\[ ((\mathbb{P}^1)^{n-m_1}, \varphi_2 \times \ldots \times \varphi_\delta, C_2 \times \ldots \times C_\delta, P'). \]

This finishes the proof of Theorem 4.7.
4.5 Proof of Theorem 4.5 when $V$ is a hypersurface

We first consider the case $\sigma \circ f \circ \sigma^{-1} = X^d$ for some $\sigma \in \text{Aut}(\mathbb{P}^1)$. By extending $K$, we may assume $\sigma \in K[X]$. For almost all $p$, $\sigma$ induces a homeomorphism from $(\mathbb{P}^1)^n(K_p)$ to itself. Hence we can assume $f(X) = X^d$. Since the conclusion of Theorem 4.5 is for almost all $p$, we can assume $V$ is an absolutely irreducible preperiodic hypersurface defined over $K$.

First, assume there exists $1 \leq i \leq n$ such that $V$ is given by $x_i = 0$ or $x_i = \infty$. By the automorphism $X \mapsto X^{-1}$ and without loss of generality, we may assume $V$ is given by $x_1 = 0$. Let $\alpha$ denote the first coordinate of $P$, since the orbit of $P$ does not intersect $V(K)$, we have $\alpha \neq 0$. For almost all $p$, the $p$-adic closure of the orbit of $P$ lies in:

$$\{(x_1, \ldots, x_n) \in (\mathbb{P}^1)^n(K_p) : v_p(x_1) = 0\}$$

which is disjoint from $V(K_p)$.

Therefore, we may assume $V \cap \mathbb{G}_m^n \neq \emptyset$. It is not difficult to prove that $V \cap \mathbb{G}_m^n$ is a translate of a subgroup of codimension 1, see [49, Remark 1.1.1]. We now denote the coordinate of each factor $\mathbb{P}^1$ as $x_1, \ldots, x_q, y_1, \ldots, y_r$ and $z_1, \ldots, z_s$ (hence $q + r + s = n$) such that $V$ is given by an equation:

$$x_1^{a_1} \cdots x_q^{a_q} = \zeta y_1^{b_1} \cdots y_r^{b_r},$$

where $a_1, \ldots, b_r$ are positive integers, and $\zeta$ is a root of unity. Actually, for $V$ to be preperiodic, we have $\zeta^{d^A} = \zeta^{d^B}$ for some $0 \leq A < B$; but we will not need this stronger fact. Write $P$ under the corresponding coordinates as:

$$P = (\alpha_1, \ldots, \alpha_q, \beta_1, \ldots, \beta_r, \gamma_1, \ldots, \gamma_s).$$

Assume some elements among the $\alpha_1, \ldots, \beta_r$ are either 0 or $\infty$, say, we have $\alpha_1 = 0$. All irreducible components of the intersection $V \cap \{x_1 = 0\}$ are described by the form $\{x_i = 0 \land x_i = \infty\}$ for $2 \leq i \leq q$, or the form $\{x_1 = 0 \land y_j = 0\}$ for some $1 \leq j \leq r$. Thus the coordinates of $P$ satisfy:

$$(\alpha_i \neq \infty \ \forall 2 \leq i \leq q) \land (\beta_j \neq 0 \ \forall 1 \leq j \leq r).$$

For every prime $p$, let $v_p(\infty) = -\infty$ (warning: the $\infty$ on the left is an element of $\mathbb{P}^1(K)$ while the $\infty$ on the right is an element of the extended real numbers). For almost all primes $p$, the $p$-adic closure of the orbit of $P$ is contained in:

$$\{(0, X_2, \ldots, Z_s) : v_p(X_i) \geq 0, \ v_p(Y_j) \leq 0 \ \forall 2 \leq i \leq q \ \forall 1 \leq j \leq r\}$$

which is disjoint from $V(K_p)$. The case, say, $\alpha_1 = \infty$ is treated similarly.

Now we can assume that all the $\alpha_1, \ldots, \beta_r$ lie in $\mathbb{G}_m(K)$. Let

$$\eta = \alpha_1^{a_1} \cdots \alpha_q^{a_q} \beta_1^{-b_1} \cdots \beta_r^{-b_r}.$$
Since the $\varphi$-orbit of $P$ does not intersect $V(K)$, we have that the $f$-orbit of $\eta$ does not contain $\zeta$. For almost all $p$, we have $\eta$ is a $p$-adic unit. By Theorem 4.10, for almost all $p$, the $p$-adic closure $C_p(\eta)$ of the orbit of $\eta$ does not contain $\zeta$. Now the $p$-adic closure of the orbit of $P$ lies in
\[ \{ (X_1, \ldots, Z_s) : X_1^{a_1} \ldots Y_r^{b_r} \in C_p(\eta) \} \]
which is disjoint from $V(K_p)$. This finishes the case $f$ is a conjugate of $X^d$.

Now we assume $f$ is a conjugate of $\pm C_d(X)$. As before, we may assume $f(X) = \pm C_d(X)$. Let $\hat{f} = \pm X^d$, and $\hat{\varphi}$ be the diagonally split morphism corresponding $\hat{f}$. Consider the morphisms:
\[ \Phi: (x_1, \ldots, x_n) \mapsto (x_1 + \frac{1}{x_1}, \ldots, x_n + \frac{1}{x_n}) \]
from $(\mathbb{P}^1)^n$ to itself. We have the commutative diagram:

\[ \begin{array}{ccc}
(P^1)^n & \xrightarrow{\phi} & (P^1)^n \\
\Phi \downarrow & & \Phi \downarrow \\
(P^1)^n & \xrightarrow{\varphi} & (P^1)^n
\end{array} \]

Extend $K$ further, we may assume there is $Q \in (\mathbb{P}^1)^n(K)$ such that $\Phi(Q) = P$. Write $\hat{V} = \Phi^{-1}(V)$. We have that the $\Phi$-orbit of $Q$ does not intersect $\hat{V}(K)$. Note that the conclusion of the theorem has been established for $\hat{f}$. Therefore, for almost all $p$, the $p$-adic closure of $O_{\hat{\varphi}}(Q)$ does not intersect $\hat{V}(K_p)$. Since $\Phi$ is finite, it maps the $p$-adic closure of $O_{\hat{\varphi}}(Q)$ onto the $p$-adic closure of $O_{\varphi}(P)$. We can conclude that the $p$-adic closure of $O_{\varphi}(P)$ does not intersect $V(K_p)$.

### 4.6 Proof of Theorem 4.5

As in Section 4.5, we first consider the case $f$ is conjugate to $X^d$, and then we may assume $f(X) = X^d$. By Theorem 4.4 and Section 4.5, we have that Theorem 4.5 is valid when $n = 1, 2$. We proceed by induction on $n$. Let $N \geq 3$ and assume that Theorem 4.5 holds for all $n < N$, we now consider the case $n = N$. As in Section 4.5, we assume $V$ is an absolutely irreducible preperiodic subvariety defined over $K$.

We first consider the case $V$ is contained in a hypersurface of the form $x_i = 0$ or $x_i = \infty$ for some $1 \leq i \leq n$. Without loss of generality, we may assume $V$ is contained in the hypersurface $x_1 = 0$. Let $\alpha$ denote the first coordinate of $P$. If $\alpha \neq 0$ then for almost all $p$, $p$-adic closure of the orbit of $P$ is contained in:
\[ \{ (x_1, \ldots, x_n) : v_p(x_1) = 0 \} \]
which is disjoint from $V(K_p)$. Hence we assume $\alpha = 0$. We now restrict to the hyperplane $x_1 = 0$ and apply the induction hypothesis.

Therefore we may assume $V \cap \mathbb{G}_m^n \neq \emptyset$. Write $P = (\alpha_1, \ldots, \alpha_n)$. We first consider the case $P \notin \mathbb{G}_m^n$. Without loss of generality, assume $\alpha_1 = 0$. We can again restrict to the hypersurface $x_1 = 0$ and apply the induction hypothesis.

Now consider the case $P \in \mathbb{G}_m^n$. For almost all $p$, the $p$-adic closure of the orbit of $P$ lies in:

$$(x_1, \ldots, x_n) \in (\mathbb{P}^1)^n(K_p) : v_p(x_i) = 0 \ \forall 1 \leq i \leq n$$

which is closed in both $(\mathbb{P}^1)^n(K_p)$ and $\mathbb{G}_m^n(K_p)$. Hence it suffices to show that for almost all $p$, the $p$-adic closure of $O_{\varphi}(P)$ in $\mathbb{G}_m^n(K_p)$ does not intersect $(V \cap \mathbb{G}_m^n)(K_p)$. This follows from the main result of [1, Theorem 4.3].
Chapter 5

Dynamical Bombieri-Masser-Zannier Height Bound

5.1 Motivation and Main Results

This section presents the second arithmetic application of the Medvedev-Scanlon theorem to a dynamical analogue of “complementary dimensional intersections” in $\mathbb{G}_m^n$ first studied by Bombieri-Masser-Zannier in [10, Theorem 1]. The story begins with the following:

**Question 5.1** (Lang, Manin-Mumford). Let $X$ be an abelian variety or the torus $\mathbb{G}_m^n$ over $\mathbb{C}$. Let $C$ be an irreducible curve in $X$. Assume $C$ is not a torsion translate of a subgroup. Is it true that there are only finitely many torsion points on $C$?

This question has an affirmative answer. When $X$ is an abelian variety, it is the Manin-Mumford conjecture first proved by Raynaud [37]. When $X = \mathbb{G}_m^n$, it is a special case of a question of Lang stated in the 1960s (see, for example, [30]) which admits many proofs as well as generalizations. For example, Bombieri, Masser and Zannier [10] obtain the following:

**Theorem 5.2** (Bombieri, Masser, Zannier). Let $C$ be an irreducible curve in $\mathbb{G}_m^n$ defined over a number field $K$ such that $C$ is not contained in any translate of a proper subgroup. Then

(a) Points in $\bigcup_V (C(\overline{K}) \cap V(\overline{K}))$ have bounded height, where $V$ ranges over all subgroup of codimension 1.

(b) The set $\bigcup_V (C(\overline{K}) \cap V(\overline{K}))$ is finite, where $V$ ranges over all subgroups of codimension 2.

While Question 5.1, and part (b) of Theorem 5.2 are instances of “unlikely intersections” (see [49]), part (a) of Theorem 5.2 is an instance of “not too likely intersections”. More
precisely, we expect that the intersection appears infinitely many times, yet remains “small” in a certain sense. A conjectural dynamical analogue of Question 5.1 has been proposed by Zhang [50] and modified by Zhang, Ghioca, and Tucker [17]. However, we are not aware of any dynamical analogue of part (a) of Theorem 5.2. By using canonical height arguments and the Medvedev-Scanlon theorem, we obtain the following:

**Theorem 5.3.** Let $K$ be a number field or a function field. Let $f \in K[X]$ be a disintegrated polynomial, and $\varphi : (\mathbb{P}^1_K)^n \to (\mathbb{P}^1_K)^n$ be the corresponding split polynomial map. Let $C$ be an irreducible curve in $(\mathbb{P}^1_K)^n$ that is not contained in any periodic hypersurface. Assume $C$ is non-vertical, by which we mean $C$ maps surjectively onto each factor $\mathbb{P}^1$ of $(\mathbb{P}^1)^n$. Then the points in

$$\bigcup_V (C(\bar{K}) \cap V(\bar{K}))$$

have bounded Weil heights, where $V$ ranges over all periodic hypersurfaces of $(\mathbb{P}^1_K)^n$.

We expect Theorem 5.3 still holds in the non-preperiodic case: $C$ is assumed to be not contained in any preperiodic hypersurface, and $V$ ranges over all preperiodic hypersurfaces. However, we could only prove a bound on the “average height” of points in the intersections (see Theorem 5.12). In fact, such bound on the average height turns out to hold for a more general polarized dynamical system (see Theorem 5.13). We prove this general result by using various constructions of heights and canonical heights coming from the Gillet-Soulé generalization of Arakelov intersection theory (see [11], [51], and [28]). At the end of this chapter, we also briefly explain why our results continue to hold for the dynamics of split polynomial maps of the form $f_1 \times \ldots \times f_n$, where $f_1, \ldots, f_n$ are disintegrated polynomials of degrees at least 2. This seemingly more general case is left to the end in order to make it easier for the readers to follow the main ideas, and more importantly because this case can be easily reduced to the diagonally split case $f \times \ldots \times f$.

Part (a) of Theorem 5.2 is only the beginning of a long story. Subsequent papers by various authors have considered bounded height results for higher dimensional complementary intersections in the torus $\mathbb{G}_m^n$ or an abelian variety. We refer the readers to [9], [21], [22] and [20] as well as the references there for more details. The results given in this chapter indicate that the above results in diophantine geometry are expected to hold, at least to some extent, in arithmetic dynamics. We will treat the dynamical analogue of higher dimensional complementary intersections in a future work. In such a higher dimensional intersection for dynamics, we also expect a bounded height result after ignoring certain “dynamically anomalous varieties” as in the diophantine context [9]. In this thesis, we will be content with intersection between a curve and preperiodic hypersurfaces in $(\mathbb{P}^1)^n$ (also see Chapter 6).

Throughout this chapter, let $f \in K[X]$ be a disintegrated polynomial. In the number field case, let $h$ denote the absolute logarithmic Weil height on $\mathbb{P}^1(\bar{K})$. In the function field case, let $h$ denote the Weil height on $\mathbb{P}^1(\bar{K})$ over $K$. We also use $h$ to denote the height on $(\mathbb{P}^1)^n(\bar{K})$ defined by $h(a_1, \ldots, a_n) = h(a_1) + \ldots + h(a_n)$. For every polynomial $P \in \bar{K}[X]$ of degree at least 2, we let $h_P$ denote the dynamical canonical height associated to $P$. We use
\( \hat{h} \) to denote the canonical height \( \hat{h}_f \). For properties of all these height functions, see [2], [24, Part B] and [42, Chapter 3].

### 5.2 Proof of Theorem 5.3

Since the projection from \( C \) to each factor \( \mathbb{P}^1 \) is finite, to show that a collection of points in \( C(\bar{K}) \) has bounded heights, it suffices to show that for some \( 1 \leq i \leq n \), all their \( x_i \)-coordinates have bounded heights. By the Medvedev-Scanlon Theorem, it suffices to show that for every \( 1 \leq i < j \leq n \), points in \( \bigcup C(\bar{K}) \cap V_{ij}(\bar{K}) \) have bounded heights where \( V_{ij} \) ranges over all periodic hypersurfaces whose equation involving \( x_i \) and \( x_j \) only. Therefore we may assume \( n = 2 \) for the rest of this section. Let \( x \) and \( y \) denote the coordinate functions on the first and second factor \( \mathbb{P}^1 \) respectively. Without loss of generality, we only need to consider the intersection with periodic curves \( V \) given by an equation of the form \( x = \zeta \) where \( \zeta \) is \( f \)-periodic, or \( y = g(x) \) where \( g \) commutes with an iterate of \( f \). Now every periodic \( \zeta \) has height bounded uniformly, we get the desired conclusion when intersecting \( C \) with curves of the form \( x = \zeta \). Note that this argument also works for all preperiodic \( \zeta \).

So we only have to consider curves \( V \) of the form \( y = g(x) \). Let \((M,N)\) denote the type of the divisor \( C \) of \( (\mathbb{P}^1)^2 \) [23, pp. 135]. Explicitly, we choose a generator \( F(x,y) \) of the (prime) ideal of \( C \) in \( \bar{K}[x,y] \), then \( F \) has degree \( M \) in \( x \) and degree \( N \) in \( y \). We have the following two easy lemmas:

**Lemma 5.4.** For every point \((\alpha, \beta)\) in \( C(\bar{K}) \), we have:

\[
| M\hat{h}(\alpha) - N\hat{h}(\beta) | \leq c_1 \sqrt{\hat{h}(\alpha)} + \hat{h}(\beta) + 1 + c_2.
\]

where \( c_1 \) and \( c_2 \) are constants independent of \((\alpha, \beta)\).

**Proof.** Let \( \tilde{C} \) denote the normalization of \( C \), we have:

\[
\tilde{C} \xrightarrow{\eta} C \xrightarrow{i} (\mathbb{P}^1_K)^2
\]

where \( \eta \) is the normalization map and \( i \) is the closed embedding realizing \( C \) as a subvariety of \( (\mathbb{P}^1_K)^2 \). The invertible sheaf \( \mathcal{L} := (\eta \circ i)^* \mathcal{O}(1,1) \) is ample on \( \tilde{C} \). Let \( \pi_1 \) and \( \pi_2 \) denote respectively the first and second projections from \( (\mathbb{P}^1_K)^2 \) to \( \mathbb{P}^1_K \). The invertible sheaves \( \mathcal{L}_1 := (\eta \circ i \circ \pi_1)^* \mathcal{O}(1) \) and \( \mathcal{L}_2 := (\eta \circ i \circ \pi_2)^* \mathcal{O}(1) \) have degrees \( N \) and \( M \), respectively.

For \( j = 1,2 \), define \( \hat{h}_j(P) = h(\pi_j \circ i \circ \eta(P)) \) for every \( P \in \tilde{C}(K) \). We also define \( \hat{h}(P) = h(i \circ \eta(P)) \) for every \( P \in \tilde{C}(K) \). Then \( h, \hat{h}_1 \) and \( \hat{h}_2 \) respectively are height functions on \( \tilde{C}(K) \) corresponding \( \mathcal{L}, \mathcal{L}_1 \) and \( \mathcal{L}_2 \). By [24, Theorem B.5.9], there is a constant \( c_1 > 0 \) depending only on the data (5.2) such that:

\[
| M\hat{h}_1(P) - N\hat{h}_2(P) | \leq c_1 \sqrt{\hat{h}(P)} + 1 \quad \forall P \in \tilde{C}(K)
\]
For every point \((\alpha, \beta) \in C(K)\), inequality (5.3) gives:
\[
|M h(\alpha) - N h(\beta)| \leq c_1 \sqrt{h(\alpha) + h(\beta)} + 1.
\] (5.4)

In terms of the canonical height function associated to \(f\), inequality (5.4) becomes:
\[
|M \hat{h}(\alpha) - N \hat{h}(\beta)| \leq c_1 \sqrt{\hat{h}(\alpha) + \hat{h}(\beta)} + 1 + c_2
\] (5.5)

where \(c_2\) only depends on \(f\) and the data (5.2).

**Lemma 5.5.** Let \(P \in \bar{K}[X]\) be a disintegrated polynomial, \(G\) a finite cyclic subgroup of linear polynomials in \(\bar{K}[X]\) such that for some positive integer \(D\), we have \(P \circ L = L^D \circ P\) for every \(L \in G\). We have:

(a) \(\hat{h}_P = \hat{h}_{L_0 P^l}\) for every \(l > 0\) and every \(L \in G\).

(b) \(\hat{h}_P(L(\alpha)) = \hat{h}_P(\alpha)\) for every \(L \in G\) and \(\alpha \in \mathbb{P}^1(K)\).

**Proof.** Since \(G\) is finite, we have:
\[
h(L(x)) = h(x) + O(1) \quad \forall x \in \bar{K} \quad \forall L \in G.
\]

For every \(k \geq 1\), we have \((L \circ P^l)^k = \tilde{L} \circ P^{kl}\) for some \(\tilde{L} \in G\). And we have:
\[
h((L \circ P^l)^k(x)) = h(P^{kl}(x)) + O(1)
\]

where \(O(1)\) is bounded independently of \(k\). Dividing both sides by \(\text{deg}(P^{kl})\) and let \(k \to \infty\) will kill off this \(O(1)\). Part (b) is proved similarly. \(\square\)

We can now finish the proof of Theorem 5.3. Let \(V\) be given by \(y = g(x)\) and \((\alpha, \beta)\) be a point in the intersection \(C \cap V\). By Proposition 3.3 and Lemma 5.5, we have \(\hat{h}(\beta) = \text{deg}(g)\hat{h}(\alpha)\). Substituting this into (5.1), we have:
\[
|M - N \text{deg}(g)|\hat{h}(\alpha) \leq c_1 \sqrt{(\text{deg}(g) + 1)\hat{h}(\alpha) + 1 + c_2}
\] (5.6)

For all sufficiently large \(\text{deg}(g)\) (for instance, we may choose \(\text{deg}(g) > \frac{2M}{N}\) so that \(N \text{deg}(g) - M > \frac{N \text{deg}(g)}{2}\)), inequality (5.6) implies that \(\hat{h}(\alpha)\) and hence \(h(\alpha)\) is bounded above by a constant depending only on \(f\) and the data (5.2). Therefore by the remark at the first paragraph of this section, \(h(\alpha, \beta)\) is bounded by a constant depending only on \(f\) and the data (5.2). Finally, by Proposition 3.3, there are only finitely many such \(g's\) of bounded degree, hence only finitely many points in the intersection \(C \cap \{y = g(x)\}\). This finishes the proof of Theorem 5.3.
5.3 Further Questions

We now gather several questions concerning the union \( \bigcup_V (C(\bar{K}) \cap V(\bar{K})) \) where \( V \) ranges over preperiodic hypersurfaces in \((\mathbb{P}^1_{\bar{K}})^n\) and \( C \) is not contained in any such hypersurface. For each \( k \geq 0 \), let \( \mathcal{P}_k \) denote the collection of all hypersurfaces \( V \) of \((\mathbb{P}^1_{\bar{K}})^n\) such that \( \varphi^k(V) \) is periodic. Thus \( \mathcal{P}_0 \) is exactly the collection of periodic hypersurfaces, and we have \( \mathcal{P}_k \subseteq \mathcal{P}_{k+1} \) for every \( k \). Apply Theorem 5.3 for \( \varphi^k(C) \), let \( \Gamma_k \) denote an upper bound for the \( f \)-canonical heights of points in

\[ \bigcup_{V \in \mathcal{P}_0} (\varphi^k(C)(\bar{K}) \cap V(\bar{K})). \]

Using

\[ \varphi^k(\bigcup_{V \in \mathcal{P}_k} (C(\bar{K}) \cap V(\bar{K}))) \subseteq \bigcup_{V \in \mathcal{P}_0} (\varphi^k(C)(\bar{K}) \cap V(\bar{K})), \]

we have that points in \( \bigcup_{V \in \mathcal{P}_k} (C(\bar{K}) \cap V(\bar{K})) \) have canonical heights bounded by \( \frac{\Gamma_k}{d^k} \) where \( d \geq 2 \) is the degree of \( f \). Heuristically speaking, suppose we could obtain a bound in Theorem 5.3 that depends, in a uniform way, on the height of \( C \), and the height of \( \varphi^k(C) \) is “essentially” the height of \( C \) multiplied by \( d^k \). Then we have that \( \Gamma_k = d^kO(1) \) where \( O(1) \) is independent of \( k \). All of these motivate the following questions. From now on, we assume \( K \) is a number field although the first two questions could be asked for function fields as well:

**Question 5.6.** Let \( f \) and \( \varphi \) be as in Theorem 5.3.

(a) Let \( C \) be an irreducible non-vertical curve in \((\mathbb{P}^1_{\bar{K}})^n\). Suppose \( C \) is not contained in an element of \( \mathcal{P}_k \). Is it true that points in

\[ \bigcup_{V \in \mathcal{P}_k} (C(\bar{K}) \cap V(\bar{K})) \]

have heights bounded independently of \( k \).

(b) Let \( C \) be an irreducible non-vertical curve in \((\mathbb{P}^1_{\bar{K}})^n\) that is not contained in any preperiodic hypersurface. Is it true that points in

\[ \bigcup_V (C(\bar{K}) \cap V(\bar{K})) \]

have bounded heights, where \( V \) ranges over all preperiodic hypersurfaces of \((\mathbb{P}^1_{\bar{K}})^n\)?

(c) Let \( C \) be as in part (b). Is it true that the union in (b) has only finitely points of bounded degree?
(d) Let $C$ be as in (b). Assume $C$ is defined over $K$. Is it true that the union in (b) has only finitely many $K$-rational points?

**Remark 5.7.** It seems to us that part (b) of Question 5.6 should have a positive answer. On the other hand, if we ask the same question when $f(X) = X^d$, then we get the statement of part (a) of Theorem 5.2 with the weaker condition that $C$ is not contained in any torsion translates of subgroups. Unfortunately, such a stronger statement (i.e. weaker condition on $C$) has easy counter-examples (see [49, pp. 25]).

It is obvious that the above questions have decreasing strength. We now focus on Question 5.8(b). We look more closely to the proof of Theorem 5.3 and see what still go through. Assume $f$, $\varphi$ and $C$ as in part (b) of Question 5.6. As before, we can assume $V$ ranges over all irreducible preperiodic hypersurfaces. Let $k \geq 0$ such that $\varphi^k(V)$ is periodic, hence given by an equation of the form, say, $x_j = g(x_i)$ where $1 \leq i < j \leq n$ (the case $\varphi^k(V)$ is given by $x_i = \zeta$ where $\zeta$ is preperiodic is easy). We can now assume $n = 2$ by projecting to the $(i,j)$-factor $(\mathbb{P}^1)^2$ of $(\mathbb{P}^1)^n$. Let $(\alpha, \beta) \in C(K) \cap V(K)$. From $f^k(\alpha) = g(f^k(\beta))$ and Lemma 5.5, we still have $h(\alpha) = \deg(g)\hat{\beta}$. Therefore inequality (5.6) still holds. We still have that $h(\alpha, \beta)$ is bounded when $\deg(g)$ is sufficiently large. Since there are only finitely many $g$'s of bounded degrees (see Proposition 3.3), one may assume that the periodic hypersurface $\{x_j = g(x_i)\}$ is fixed. Our discussions so far implies that Question 5.6(b) is equivalent to the following:

**Question 5.8.** Let $f$, $\varphi$ and $C$ be as in Question 5.6(b). Let $W$ be a fixed irreducible periodic hypersurface of $(\mathbb{P}^1_K)^n$. For $k \geq 0$, write $\varphi^{-k}(W)$ to denote $(\varphi^k)^{-1}(W)$. Is it true that points in $\bigcup_{k \geq 0} C(K) \cap \varphi^{-k}(W)(\overline{K})$ have bounded heights?

We now focus on Question 5.8. We could only prove a weaker result, namely points in $C(K) \cap \varphi^{-k}(W)(\overline{K})$ have bounded “average heights” independent of $k$ (see Section 5.5). Such a result is motivated by examples given in the next section.

### 5.4 Examples

Let $f$, $\varphi$, $W$ and $C$ be as in Question 5.8. We may assume $n = 2$ and $W$ is given by $y = g(x)$ where $g$ commutes with an iterate of $f$. In this section, we look at the case when $C$ is a rational curve parametrized by $(P(t), Q(t))$ where $P$ and $Q$ are polynomials with coefficients in $K$. Question 5.8 asks whether roots of $f^k \circ Q = g \circ f^k \circ P$ have heights bounded independently of $k$. Note that if $\alpha$ is such a root then $h(Q(\alpha)) = \deg(g)\hat{h}(P(\alpha))$ by Lemma 5.5. Therefore $|\deg(Q) - \deg(g)\deg(P)|h(\alpha)$ is bounded independently of $k$. Hence if $\deg(g)\deg(P) \neq \deg(Q)$ then Question 5.8 has an affirmative answer. For the rest of this section, we may assume $\deg(g)\deg(P) = \deg(Q)$.

Since $g$ commutes with an iterate $f^l$ of $f$, we may look at $l$ collections of equations of the form

$$f^{ql+r} \circ Q = g \circ f^{ql+r} \circ P = f^{ql} \circ g \circ f^r \circ P$$

for $0 \leq q$,
for each $0 \leq r < l$. Replacing $(P, Q)$ by $(g \circ f^r \circ P, f^r \circ Q)$, we may assume $g(x) = x$ (i.e. $V_0$ is the diagonal), and hence $\deg(P) = \deg(Q)$. For every $k \geq 0$, put $G_k = f^k \circ P - f^k \circ Q$. We need to show that roots of $G_k$ have heights bounded independently of $k$. By making a linear change, we can assume $f$ has the following form:

$$f(X) = X^d + a_{d-2}X^{d-2} + \ldots + a_0.$$  

Write $f(X)$ into the form $f(X) = X^D R(X^M)$ where $R(X) \in K[X]$, $D, M \geq 0$, and $M$ is maximal. We will assume that $R(0) \neq 0$ so that the triple $(D, M, R)$ is unique. It follows from [4], and [41] that the group $\Sigma_f$ of linear automorphisms of the Julia set of $f$ is exactly the group of rotations $L(X) = \zeta X$, where $\zeta$ is an $(M-1)^{\text{th}}$ root of unity. Furthermore, we have $f \circ L = L^D \circ f$ for every $L \in \Sigma_f$. This implies that every curve in $(\mathbb{P}^1)^2$ of the form $y = L(x)$ where $L \in \Sigma_f$ is preperiodic under $f \times f$. The following lemma is well-known, and we include a quick proof due to the lack of an immediate reference:

**Lemma 5.9.** If $\zeta_1$ and $\zeta_2$ are two roots of unity such that $f(\zeta_1 X) = \zeta_2 f(X)$ then $\zeta_1 X \in \Sigma_f$ (equivalently $\zeta_1^M = 1$), and $\zeta_2 = \zeta_1^D$.

**Proof.** Write $f(X) = X^D R(X^M)$ as above. From $f(\zeta_1 X) = \zeta_2 f(X)$, we have:

$$\zeta_1^D X^D R(\zeta_1^M X^M) = \zeta_2 X^D R(X^M).$$

This implies:

$$R(uX) = vR(X),$$

where $u = \zeta_1^M$ and $v = \zeta_2 \zeta_1^{-D}$. Let $n_1 < n_2 < \ldots < n_\ell$ be non-negative integers such that $X^{n_1}, \ldots, X^{n_\ell}$ are all the terms in $R(X)$ having non-zero coefficients. Since $f(X) \neq X^d$, we have that $\ell \geq 2$. By the maximality of $M$, we have that $\gcd(n_2 - n_1, \ldots, n_\ell - n_{\ell-1}) = 1$. The identity $R(uX) = vR(X)$ implies $u^{n_1} = \ldots = u^{n_\ell}$, hence $u$ is a root of unity whose order divides $n_2 - n_1, \ldots, n_\ell - n_{\ell-1}$. Therefore $u = 1$, hence $v = 1$. \hfill $\square$

Now we can prove the following:

**Proposition 5.10.** (a) There is a constant $c_3$ such that

$$\deg(G_k) \geq c_3 d^k \quad \forall k.$$  

(b) There is a constant $c_4$ such that the affine height of $G_k$ ([24, Part B]) satisfies:

$$h(G_k) \leq c_4 d^k \quad \forall k.$$  

(c) The average height of the roots of $G_k$ are bounded independently of $k$: there is $c_5$ such that:

$$\frac{1}{\deg(G_k)} \sum_{G_k(\alpha) = 0} h(\alpha) \leq c_5 \quad \forall k,$$ 

where we allow repeated roots to appear multiple times in $\sum$. 


Proof. For part (a): if there are $k_1 < k_2$ and roots of unity $\zeta_1, \zeta_2$ such that:

$$f^{k_i} \circ Q = \zeta_i f^{k_i} \circ P \text{ for } i = 1, 2,$$

then we have that

$$f^{k_2-k_1}(\zeta_1 X) = \zeta_2 f^{k_2-k_1}(X).$$

By Lemma 5.9 and the fact that $\Sigma_f = \Sigma_{f^{k_2-k_1}}$, we have that $\zeta_1 X \in \Sigma_f$. By the discussion right before Lemma 5.9, the curve $\phi^{k_1}(C)$ which is given by $y = \zeta_1 x$ is preperiodic, contradiction. Therefore, there exists $\mu$ such that $f^k \circ Q$ is not a root of unity for $k \geq \mu$.

Write:

$$f^{k-\mu}(X) = X^{d^{k-\mu}} + b_{d^{k-\mu}-2}X^{d^{k-\mu}-2} + ...$$

We have (this is the only place where we do not follow our convention on notation: $N$ in the exponent means the usual “raising to the $N$th power” instead of “taking the $N$th iterate”):

$$(f^\mu \circ Q)^N - (f^\mu \circ P)^N = \prod_{\zeta^N = 1} (f^\mu \circ Q - \zeta f^\mu \circ P).$$

Since at most one factor has degree lower than $d^\mu \deg(P)$, and that factor is a nonzero polynomial, we have:

$$\deg((f^\mu \circ Q)^N - (f^\mu \circ P)^N) \geq (N - 1)d^\mu \deg(P).$$

Therefore:

$$\deg(G_k) = \deg(f^{k-\mu} \circ f^\mu \circ Q - f^{k-\mu} \circ f^\mu \circ Q) \geq (d^{k-\mu} - 1)d^\mu \deg(P).$$

This finishes part (a).

For part (b), it suffices to show there are constants $\epsilon_1$ and $\epsilon_2$ such that $h(f^k \circ P) \leq \epsilon_1 d^k$ and $h(f^k \circ Q) \leq \epsilon_2 d^k$ for every $k$. By similarity, we only need to prove the existence of $\epsilon_1$.

Let $r_1, ..., r_{d^k}$ denote the roots of $f^k$. Since $\hat{h}_f(r_i) = \frac{\hat{h}_f(0)}{d^k}$, we have:

$$\sum_{i=1}^{d^k} h(r_i) = \hat{h}_f(0) + O(1)d^k \quad (5.7)$$

where $O(1)$ only depends on $f$ (since we change from canonical height to Weil height). From $f^k \circ P = \prod_{i=1}^{d^k} (P - r_i)$, and [24, Proposition B.7.2] we have:

$$h(f^k \circ P) \leq \sum_{i=1}^{d^k} (h(P - r_i) + (\deg(P) + 1) \log 2)$$

$$\leq \sum_{i=1}^{d^k} (h(P) + h(r_i) + (\deg(P) + 2) \log 2)$$

$$= \hat{h}_f(0) + d^k (h(P) + (\deg(P) + 2) \log 2 + O(1))$$
where the last equality follows from (5.7), so the error term $O(1)$ only depends on $f$. Finally, part (c) follows from part (a), part (b) and [8, Theorem 1.6.13].

Part (c) of Proposition 5.10 only gives us an upper bound (independent of $k$) for the average of the heights of roots of $G_k$ instead of the height of every root. Now suppose there is a constant $c_6$ (independent of $k$) such that for every $k$, every root $\alpha$ of $G_k$ that is not a root of $G_{k-1}$ has degree at least $c_6 d_k$ over $K$ then we are done. The reason is that there are at least $c_6 d_k$ conjugates of $\alpha$ and all contribute the same height to the average. It is usually the case in the dynamics of disintegrated $f$ that every irreducible factor (in $K[\overline{X}]$) of $G_k$ has a large degree unless it has already been a factor of $G_{k-1}$. However, while such phenomena appear in practice, it seems to be a very difficult problem to prove that such lower bounds on the degrees hold in general. We conclude this section by cooking up a specific instance in which all irreducible factors of $\frac{G_k}{G_{k-1}}$ have large degrees thanks to the Eisenstein criterion.

**Proposition 5.11.** Let $d \geq 2$ and let $p > d$ be a prime. Let $f(X) = X^d + p$, and $C$ be the curve $y = x + p$ in $(\mathbb{P}_K^1)^2$. Then $C$ is non-preperiodic and points in $\bigcup V \subset C(\overline{K}) \cap V(\overline{K})$ have bounded heights, where $V$ ranges over all preperiodic curves of $(\mathbb{P}_K^1)^2$.

**Proof.** By Theorem 3.2 and Proposition 3.3, non-preperiodicity of $C$ is equivalent to $f^k(x) \neq \zeta f^k(x + p)$ for every $k$, and this is obvious. Hence $C$ is non-preperiodic.

We have:

$$G_k = f^k(x + p) - f^k(x) = \prod_{\zeta^d = 1} (f^{k-1}(x + p) - \zeta f^{k-1}(x)).$$

By the reduction from part (b) of Question 5.6 to Question 5.8, it suffices to show that for every periodic $W$, points in $\bigcup_{k \geq 0} C(\overline{K}) \cap \varphi^{-k}(W)(\overline{K})$ have bounded heights. By the argument in the beginning of this section, we may assume $W$ is the diagonal. Hence it suffices to show that roots of $G_k$ have bounded heights independent of $k$. By Eisenstein’s criterion, $f^{k-1}(x + p) - \zeta f^{k-1}(x)$ is irreducible (over $\mathbb{Q}(\zeta)$) when $\zeta \neq 1$. Then by Proposition 5.10 and the discussion after it, we get the desired conclusion.

### 5.5 The Bounded Average Height Theorem

**The Statements**

In this subsection, we prove that the average bounded height result in Proposition 5.10 holds for an arbitrary polarized dynamical system (see Theorem 5.13). We have the following:

**Theorem 5.12.** Let $f$, $n$ and $\varphi$ be as in Theorem 5.3. Let $C$ be an irreducible curve in $(\mathbb{P}_K^1)^n$ such that its projection to each factor $\mathbb{P}_K^1$ is onto. There exists a constant $c_7$ such that for every irreducible preperiodic hypersurface $V$ in $(\mathbb{P}_K^1)^n$ that does not contain $C$, the average height of points in $C(\overline{K}) \cap V(\overline{K})$ is bounded above by $c_7$. More precisely, define:

$$C_K.V = m_1 P_1 + \ldots + m_l P_l$$
where \( C(\bar{K}) \cap V(\bar{K}) = \{ P_1, \ldots, P_l \} \) and \( m_1, \ldots, m_l \) are the corresponding intersection multiplicities. Then we have:

\[
\sum_{i=1}^{l} m_i h(P_i) \leq c_7.
\]

(5.8)

As in the proof of Theorem 5.3, we can simply reduce to the case \( n = 2 \). Then Theorem 5.12 is a special case of the following:

**Theorem 5.13.** Let \( X \) be a projective scheme over \( K \) such that \( X_{\bar{K}} \) is normal and irreducible, \( H \) a closed subscheme of \( X \) such that \( H_{\bar{K}} \) is an irreducible hypersurface. Assume the line bundle \( L \) associated to \( H \) is very ample. Let \( d \geq 2 \), and let \( \varphi \) be a \( K \)-morphism from \( X \) to itself such that \( \varphi^*L \cong L^d \). Fix a height \( \hat{h} \) on \( X(\bar{K}) \) corresponding to a very ample line bundle. There exists \( c_8 \) such that for every irreducible \( \varphi \)-preperiodic curve \( V \) of \( X_{\bar{K}} \) not contained in \( H_{\bar{K}} \), the average height of points in \( H(\bar{K}) \cap V(\bar{K}) \) is bounded above by \( c_8 \). More precisely, write:

\[
H_{\bar{K}} \cdot V_{\bar{K}} = m_1 P_1 + \ldots + m_2 P_2
\]

where \( H(\bar{K}) \cap V(\bar{K}) = \{ P_1, \ldots, P_l \} \) and \( m_1, \ldots, m_l \) are the corresponding multiplicities. Then we have:

\[
\frac{\sum_{i=1}^{l} m_i \hat{h}(P_i)}{\sum_{i=1}^{l} m_i} \leq c_8.
\]

(5.9)

We now focus on proving Theorem 5.13. Note the amusing change that we now concentrate on the intersection of a fixed hypersurface with an arbitrary preperiodic curve. We regard \( X \) as a closed subvariety of \( \mathbb{P}^N_{\overline{K}} \) by choosing a closed embedding associated to \( H \). Let \( h \) denote the Weil height on \( \mathbb{P}^N_{\overline{K}} \) as well as its restriction on \( X(\bar{K}) \). We may prove Theorem 5.13 with \( \hat{h} \) replaced by \( h \) since there exists \( M \) such that \( \hat{h} < M h + O(1) \) where the error term \( O(1) \) is uniform on \( X(\bar{K}) \). The main ingredients of the proof of Theorem 5.13 are the arithmetic Bézout’s theorem by Bost-Gillet-Soulé [11], and the construction of the canonical height for subvarieties by Zhang [51] and Kawaguchi [28].

**Proof of Theorem 5.13**

Let \( V \) be a \( \varphi \)-preperiodic curve in \( X_{\bar{K}} \). Let \( F \) be a finite extension of \( K \) such that \( V \) is defined over \( F \). Write \( \mathcal{O} = \mathcal{O}_K \) to denote the ring of integers of \( K \), and \( \pi \) to denote the base change morphism \( \mathbb{P}^N_F \rightarrow \mathbb{P}^N_K \). As in [11, pp. 946–947], we let \( \overline{E} \) denote the trivial hermitian vector bundle of rank \( N + 1 \) on \( \text{Spec}(\mathcal{O}) \) and equip the canonical line bundle \( \mathcal{M} := \mathcal{O}(1) \) of \( \mathbb{P}^N_{\mathcal{O}} \) with the quotient metric \( m \). We denote \( \mathcal{M} = (\mathcal{M}, m) \). The pull-back of \( \mathcal{M} \) to \( X \) is isomorphic to the line bundle \( L \).

For \( 0 \leq p \leq N + 1 \), for any cycle \( \mathcal{Z} \in Z_p(\mathbb{P}^N_{\mathcal{O}}) \) of dimension \( p \), following [11, pp. 946], we define the Faltings’ height of \( \mathcal{Z} \) to be the real number:

\[
h_{Fal}(\mathcal{Z}) = \text{deg} \left( \hat{c}_1(\mathcal{M})^p | \mathcal{Z} \right)
\]

(5.10)
where $\hat{c}_1(\mathcal{M})$ is the first arithmetic Chern class of $\mathcal{M}$, and $\deg$ is the arithmetic degree map as defined in [11].

For $0 \leq p \leq N$, for every cycle $Z \in Z_p(\mathbb{P}^N_K)$, let $Z$ denote the closure of $Z$ in $\mathbb{P}^N_{\hat{\mathcal{O}}}$. We define the Faltings' height of $Z$ to be:

$$h_{\text{Fal}}(Z) := h_{\text{Fal}}(\bar{Z}).$$

(5.11)

If $Z \in Z_p(\mathbb{P}^N_K)$, we let $K'$ be a finite extension of $K$ so that $Z$ is defined over $K'$, i.e. $Z$ is the pull-back of a cycle $Z' \in Z_p(\mathbb{P}^N_{K'})$. Let $\rho$ denote the base change morphism from $\mathbb{P}^N_{K'}$ to $\mathbb{P}^N_{K}$. We then define the Faltings' height of $Z$ to be:

$$h_{\text{Fal}}(Z) := \frac{1}{[K':K]}h_{\text{Fal}}(\rho_*Z').$$

(5.12)

This is independent of the choice of $K'$.

For $0 \leq p \leq N + 1$, for every cycle $\mathcal{Z} \in Z_p(\mathbb{P}^N_{\hat{\mathcal{O}}})$, we have the following Bost-Gillet-Soulé projective height of $\mathcal{Z}$ [11, pp. 964]:

$$h_{\text{BGS}}(\mathcal{Z}) = \deg(\hat{c}_p(\bar{Q}) \mid \mathcal{Z})$$

(5.13)

where $\bar{Q}$ is the hermitian vector bundle defined as in [11, pp. 964], and $\hat{c}_p$ is the $p$th arithmetic Chern class of $\bar{Q}$.

For $0 \leq p \leq N$, for every cycle $Z \in Z_p(\mathbb{P}^N_{K})$, we define the Bost-Gillet-Soulé height of $Z$ to be:

$$h_{\text{BGS}}(Z) := h_{\text{BGS}}(\bar{Z}).$$

(5.14)

If $Z \in Z_p(\mathbb{P}^N_{K})$, we let $K'$ be a finite extension of $K$ over which $Z$ is defined by $Z' \in Z_p(\mathbb{P}^N_{K'})$. Let $\rho$ be the base change morphism as above, we define:

$$h_{\text{BGS}}(Z) := \frac{1}{[K':K]}h_{\text{BGS}}(\rho_*Z').$$

(5.15)

This is independent of the choice of $K'$.

Proposition 4.1.2 in [11] in which the authors compare the Faltings' height and the Bost-Gillet-Soulé projective height yields the following:

**Proposition 5.14.** For $0 \leq p \leq N$, for any cycle $Z \in Z_p(\mathbb{P}^N_{K})$, define $\deg_K(Z) = \deg_{\hat{\mathcal{O}}(1),K}(\bar{Z})$ as in [11, pp. 964]. We have:

$$h_{\text{BGS}}(Z) = h_{\text{Fal}}(Z) - [K:Q]\sigma_p \deg_K(Z),$$

(5.16)

where $\sigma_p$ is the Stoll number (see, for example, [11, pp. 922]).

The arithmetic Bézout theorem [11, Theorem 4.2.3] implies the following:
Proposition 5.15. Let \( Y \in \mathbb{Z}_{N-1}(\mathbb{P}_K^N) \) and \( Z \in \mathbb{Z}_1(\mathbb{P}_K^N) \) be two cycles intersecting properly in \( \mathbb{P}_K^N \). We have:

\[
 h_{BGS}(Y.Z) \leq \deg_K(Z)h_{BGS}(Y) + h_{BGS}(Z)\deg_K(Y) + [K : \mathbb{Q}]a(N, N, 2)\deg_K(Y)\deg_K(Z)
\]

(5.17)

where \( a(N, N, 2) \) is the constant defined in [11, pp. 971].

To prove Proposition 5.15, note the following:

\[
 h_{BGS}(Y.Z) := h_{BGS}(YZ) \leq h_{BGS}(\bar{Y}Z)
\]

because the closure \( \bar{Y}Z \) of \( Y.Z \) is contained in \( \bar{Y}Z \). Then we bound \( h_{BGS}(\bar{Y}Z) \) from above by the right hand side of (5.17) thanks to [11, Theorem 4.2.3].

Let \( H' \) denote the hyperplane of \( \mathbb{P}_K^N \) whose restriction to \( X \) is \( H \). Define \( V' = \frac{V}{\sum_{i=1}^t m_i} \) as a pure cycle (with rational coefficients) in \( \mathbb{P}_F^N \). By the classical Bézout’s theorem [15, Chapter 8], we have:

\[
 \deg_K(\pi_*V') = [F : K]\deg_F(V') = \frac{[F : K]\deg_F(V)}{\deg_K(H'_K.V_K)} = \frac{[F : K]\deg_F(V)}{\deg_F(H'_F)} = [F : K].
\]

(5.18)

\[
 \deg_K(H'.\pi_*V') = [F : K].
\]

(5.19)

Applying Proposition 5.15 for the cycles \( H' \) and \( \pi_*V' \) together with (5.18) and (5.19), we have:

\[
 h_{BGS}(H'.\pi_*V') \leq [F : K]h_{BGS}(H') + h_{BGS}(\pi_*V') + [F : \mathbb{Q}]a(N, N, 2).
\]

(5.20)

By using Proposition 5.14, (5.18), (5.19) and the fact that \( \sigma_0 = 0 \), we can replace \( h_{BGS} \) by \( h_{Fal} \) in (5.20) to get:

\[
 h_{Fal}(H'.\pi_*V') \leq [F : K](h_{Fal}(H') - [K : \mathbb{Q}]\sigma_{N-1}) + h_{Fal}(\pi_*V') - [F : \mathbb{Q}]\sigma_1 + [F : \mathbb{Q}]a(N, N, 2).
\]

(5.21)

Therefore

\[
 h_{Fal}(H'.\pi_*V') \leq [F : K]h_{Fal}(H') + h_{Fal}(\pi_*V') + [F : \mathbb{Q}]c_{10},
\]

(5.22)

where \( c_{10} = a(N, N, 2) - \sigma_1 - \sigma_{N-1} \) is an explicit constant depending only on \( N \).

Dividing both sides of (5.22) by \([F : \mathbb{Q}]\), and using \( h_{Fal}(\pi_*V') = [F : K]h_{Fal}(V') \), we have:

\[
 \frac{h_{Fal}(H'.\pi_*V')}{[F : \mathbb{Q}]} \leq \frac{h_{Fal}(H')}{[K : \mathbb{Q}]} + \frac{h_{Fal}(V')}{[K : \mathbb{Q}]} + c_{10}
\]

(5.23)
From $H'_K \cdot V'_K = \sum_{i=1}^{l} m_i P_i \sum_{i=1}^{l} m_i$, we have:

$$\frac{h_{Fal}(H'_K \cdot \pi'_{*} V''')} {[F : K]} = \frac{\sum_{i=1}^{l} m_i h_{Fal}(P_i)} {\sum_{i=1}^{l} m_i} \quad (5.24)$$

Recall that $h$ denotes the absolute Weil height on $\mathbb{P}^N(\overline{K})$ (see the paragraph right after Theorem 5.13). Note that $h_{Fal}$ on $\mathbb{P}^N(\overline{K})$ is also a choice of a Weil height (relative over $K$) corresponding the canonical line bundle $\mathcal{O}(1)$. Hence there exists a constant $c_{11}$ such that:

$$\left| h(P) - \frac{h_{Fal}(P)} {[K : \mathbb{Q}]} \right| \leq c_{11} \quad \forall P \in \mathbb{P}^N(\overline{K}). \quad (5.25)$$

From (5.23), (5.24) and (5.25), we have:

$$\sum_{i=1}^{l} m_i h(P_i) \sum_{i=1}^{l} m_i \leq \frac{h_{Fal}(V'')} {[K : \mathbb{Q}]} + \frac{h_{Fal}(H')} {[K : \mathbb{Q}]} + c_{10} + c_{11}. \quad (5.26)$$

To finish the proof of Theorem 5.13, it remains to show that $\frac{h_{Fal}(V'')} {[K : \mathbb{Q}]}$ is bounded independently of $V$. We will use the canonical height $h_{\varphi,L}$ constructed by Zhang [51] and generalized by Kawaguchi [28]. We have the following special case of their construction:

**Proposition 5.16.** There is a height function $h_{\varphi,L}$ on effective cycles in $Z_1(X_K)$ satisfying the following properties:

(a) If $Z$ is a preperiodic curve in $X_K$ then $h_{\varphi,L}(Z) = 0$.

(b) There exists a constant $c_{12}$ such that for every curve $Z$ in $X_K$, we have:

$$\left| h_{\varphi,L}(Z) - \frac{h_{Fal}(Z)} {2[K : \mathbb{Q}] \deg_{\overline{K}}(Z)} \right| < c_{12}$$

Part (a) follows from [51, Theorem 2.4], and part (b) follows from [28, Theorem 2.3.1]. The preperiodicity of $V$ together with Proposition 5.16 yield:

$$\frac{h_{Fal}(V'')} {[K : \mathbb{Q}]} = \frac{h_{Fal}(V)} {[K : \mathbb{Q}] \deg_{\overline{K}}(V)} < 2c_{12}$$

which finishes the proof of Theorem 5.13.
5.6 Split Polynomial Maps Associated to Disintegrated Polynomials

We briefly explain why Theorem 5.3 and Theorem 5.12 remain valid for the dynamics of maps of the form $\Phi = f_1 \times \ldots \times f_n : (\mathbb{P}^1_K)^n \rightarrow (\mathbb{P}^1_K)^n$, where $f_1, f_2, \ldots, f_n$ are disintegrated polynomials of degrees at least 2. This more general case can be easily reduced to the case of diagonally split polynomials maps $\varphi = f \times \ldots \times f$ considered throughout this thesis.

**Theorem 5.17.** Let $n \geq 2$, and let $f_1, \ldots, f_n \in K[X]$ be disintegrated polynomials of degrees at least 2. Then Theorem 5.3 and Theorem 5.12 still hold for the dynamics of the split polynomial map $\Phi = f_1 \times \ldots \times f_n$.

In fact, Medvedev and Scanlon (see Proposition 2.21 and Fact 2.25 in [31]) prove that every irreducible $\Phi$-preperiodic hypersurface of $(\mathbb{P}^1_K)^n$ has the form $\pi_{ij}^{-1}(Z)$ where $1 \leq i < j \leq n$, $\pi_{ij}$ is the projection onto the $(i,j)$-factor $(\mathbb{P}^1)^2$ and $Z$ is an $f_i \times f_j$-preperiodic curve in $(\mathbb{P}^1_K)^2$. Therefore we can reduce to the case $n = 2$. If every periodic curve of $(\mathbb{P}^1)^2$ under $f_1 \times f_2$ has the form $\zeta \times \mathbb{P}^1$ or $\mathbb{P}^1 \times \zeta$ then we are done. If there is a preperiodic curve that does not have such forms, by [31, Proposition 2.34] there exist polynomials $p_1, p_2$ and $q$ such that $f_1 \circ p_1 = p_1 \circ q$, and $f_2 \circ p_2 = p_2 \circ q$. In other words, we have the commutative diagram:

```
\begin{array}{ccc}
(\mathbb{P}^1)^2 & \xrightarrow{(q,q)} & (\mathbb{P}^1)^2 \\
(p_1,p_2) \downarrow & & (p_1,p_2) \downarrow \\
(\mathbb{P}^1)^2 & \xrightarrow{\Phi} & (\mathbb{P}^1)^n
\end{array}
```

For every $\Phi$-preperiodic curve $V$ in $(\mathbb{P}^1)^2$, we have that every irreducible component of $(p_1,p_2)^{-1}(V)$ is $(q,q)$-preperiodic. Moreover, if $V$ is $\Phi$-periodic, at least one irreducible component of $(p_1,p_2)^{-1}(V)$ is $(q,q)$-periodic. Furthermore, it is a consequence of Ritt’s theory of polynomial decomposition that if $f_1 \circ p_1 = p_1 \circ q$, and $f_1$ is disintegrated then $q$ is also disintegrated. Hence we can reduce to the case of diagonally split polynomial maps treated earlier.
Chapter 6

Further Work in Progress

We conclude the thesis with this brief chapter to describe some further questions and work in progress.

6.1 Dynamical Bombieri-Masser-Zannier in Higher Complementary Dimensional Intersection.

Let $K$, $f$, and $n$ be as in Theorem 5.3. Throughout this section, our ambient variety will be $\mathbb{A}^n$, and $\varphi = f \times \ldots \times f$ is regarded as a self-map of $\mathbb{A}^n$. For simplicity we assume that $K$ is a number field. For the diophantine geometry of $\mathbb{G}_m^n$, Bombieri, Masser, and Zannier have proposed a Bounded Height Conjecture for arbitrary “complementary dimensional intersections” [9]. This conjecture has been proved by Habegger [22]. In this section, we briefly address the comments made in Section 5.1 concerning bounded height results in arithmetic dynamics when we intersect a variety $C$ of dimension $D \geq 1$ with $\varphi$-periodic subvarieties $V$ of codimension $D$ in $\mathbb{A}^n$. One reason for taking $\mathbb{A}^n$ instead of $(\mathbb{P}^1)^n$ as our ambient variety is that $\infty$ is a fixed point of $f$, hence there seems to be more “trivial” periodic subvarieties inside $(\mathbb{P}^1)^n$ which provide “trivial” counter-examples to our bounded height problem. In our work in progress, the case $D = n - 1$ (i.e. intersecting a fixed hypersurface with all periodic curves) could be done without much difficulty. We could prove the following:

Theorem 6.1. Let $X$ be an irreducible hypersurface in $\mathbb{A}^n_Q$ satisfying the following 2 conditions:

(H1) $X$ does not contain any $\varphi$-periodic curves.

(H2) For every (ordered) subset $J$ of $\{1, \ldots, n\}$ such that $|J| = n - 1$, for every $\varphi_J$-periodic curve $W$ in $\mathbb{A}^J$, and every $\varphi_J$-wandering point $a \in W(\overline{\mathbb{Q}})$, we have that $X$ does not contain $\{a\} \times \mathbb{A}^1$. Here $\varphi_J = f \times \ldots \times f$ is the corresponding self-map of $\mathbb{A}^J$, and we identify $\mathbb{A}^n = \mathbb{A}^J \times \mathbb{A}^1$. 

Then the set:

\[ \bigcup_{V} X(\overline{\mathbb{Q}}) \cap V(\overline{\mathbb{Q}}) \]

has bounded Weil heights, where \( V \) ranges over all periodic curves of \( \mathbb{A}^n_{\overline{\mathbb{Q}}} \).

Remark 6.2. When \( n = 2 \), Theorem 6.1 is exactly the same as Theorem 5.3.

Remark 6.3. It is obvious why Condition (H1) is necessary. We explain why Condition (H2) is also necessary, as follows. Without loss of generality, let \( J = \{1, \ldots, n-1\} \), \( W \) a \( \varphi_j \)-periodic curve in \( \mathbb{A}^{n-1} \), and \( a = (a_1, \ldots, a_{n-1}) \in W \) where \( a_1 \) is \( f \)-wandering. Assume that the hypersurface \( X \) of \( \mathbb{A}^n \) contains \( \{a\} \times \mathbb{A}^1 \). For every \( m \geq 1 \), consider the curve \( V_m \) in \( \mathbb{A}^n \) defined as follows:

\[ V_m := \{ (x_1, \ldots, x_n) : (x_1, \ldots, x_{n-1}) \in W, \ x_n = f^m(x_1) \} \]

It is immediate that \( V_m \) is \( \varphi \)-periodic, and the point \( (a_1, \ldots, a_{n-1}, f^m(a_1)) \) is contained in \( X \cap V_m \). Therefore heights of points in \( \bigcup_m X \cap V_m \) are not bounded.

It seems that when we go further to investigate the dynamical bounded height problem for intersections between \( C \) of dimension \( 1 < D < n-1 \) and periodic subvarieties of codimension \( D \), some “dynamical Manin-Mumford” problem would inevitably arise. A similar issue also appears in the diophantine setting, yet, fortunately the “Manin-Mumford type” problem for \( \mathbb{G}^n_m \) is relatively easy to solve. On the other hand, analogous problems for the dynamics of \( \varphi \) on \( \mathbb{A}^n \) seem to be very hard due to the lack of an algebraic group structure comparable to \( \varphi \). Very little is known about the dynamical Manin-Mumford problem, and we refer the readers to [50] and [17] for more details.

### 6.2 Medvedev-Scanlon Classification for Rational Maps and Applications

For the rest of this section, let \( F \) be an algebraically closed field of characteristic 0, let \( f(X) \in F(X) \) be a rational map of degree \( d \geq 2 \). Let \( n \geq 2 \), and \( \varphi = f \times \ldots \times f \) be the corresponding self-map of \( (\mathbb{P}^1)^n \). We have the following definition:

**Definition 6.4.** The rational map \( f(X) \) is said to be special if it is linearly conjugate to \( X^d \), \( \pm C_d(X) \) or a Lattès map. Otherwise, \( f \) is said to be disintegrated.

It is natural to ask the following question:

**Question 6.5.** Does the Medvedev-Scanlon classification of \( \varphi \)-periodic subvarieties (i.e. Theorem 3.2) remain valid when \( f(X) \) is a disintegrated rational map?
In a joint work in progress with Michael Zieve, we expect an affirmative answer to Question 6.5. Then we obtain its formal consequences such as the dynamical Bombieri-Masser-Zannier height bound theorem, and an effective construction of an algebraic point having Zariski dense orbit confirming a conjecture of Zhang for the dynamics of \( \varphi \) (see [31, Section 7] for the polynomial case).

Moreover, we could prove that for \( d \geq 4 \), for an explicit and generic collection of rational maps \( f(X) \), Question 6.5 has an affirmative answer. In fact, Question 6.5 could be reduced to the study of the system of two functional equations:

\[
\begin{align*}
    f_k \circ p &= p \circ r, \\
    f_k \circ q &= q \circ r
\end{align*}
\]

where \( k \geq 1 \), and \( p, q, r \in F(X) \) are non-constant rational functions. For \( d \geq 4 \), and a generic collection of \( f(X) \), we could completely solve the function equation \( f^k \circ p = p \circ r \). More precisely, we could prove the following:

**Theorem 6.6.** Let \( f(X) \in F(X) \) having degree \( d \geq 4 \). Assume that \( f \) is simply branched, which means \( f \) has \( 2d - 2 \) distinct critical values. Let \( k \geq 1 \). Then every non-constant solution \( p, r \in F(X) \) of the functional equation

\[
f^k \circ p = p \circ r
\]

has the form: \( p = f^m \circ u \), \( r = u^{-1} \circ f^k \circ u \), where \( m \geq 0 \) and \( u \in F(X) \) has degree 1.

Then we have the following Medvedev-Scanlon classification:

**Corollary 6.7.** Let \( n \geq 2 \), and \( x_1, \ldots, x_n \) denote the coordinate functions of each factor of \((\mathbb{P}^1)^n\). For \( 1 \leq i \leq n \), let \( f_i(X) \in F(X) \) be a simply branched rational map of degree \( d_i \geq 4 \). Let \( \varphi = f_1 \times \ldots \times f_n \) be the corresponding self-map of \((\mathbb{P}^1)^n\). Let \( Z \) be a \( \varphi \)-periodic subvariety of period \( k \). Then \( Z \) is given by equations of the form:

(a) \( x_i = \zeta \) for some \( 1 \leq i \leq n \) and \( \zeta \) is \( f_i \)-periodic of period \( k \).

(b) \( x_i = \psi(x_j) \) for some \( 1 \leq i \neq j \leq n \), and \( \psi(X) \in F(X) \) satisfies \( f^k_i \circ \psi = \psi \circ f^k_j \).

Furthermore, by Theorem 6.6, this only happens when \( f^k_i \) and \( f^k_j \) are conjugate to each other.

**Remark 6.8.** The collection of simply branched maps of degree \( d \geq 2 \) is generic in the sense that it contains a Zariski open set in the moduli space of Rat\_\(d\) of rational maps of degree \( d \) (see [35]).

Our solution of the functional equation in Theorem 6.6 has applications not only to the Medvedev-Scanlon classification, but also to the main results by Ghioca, Tucker, and Zieve [16], [18] on the dynamical Mordell-Lang problem.
Bibliography


BIBLIOGRAPHY


