Algebraic Dynamics

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Preface

This document provides an introduction to algebraic dynamics, focusing on the study of dynamical systems defined by algebraic maps on algebraic varieties. The main interesting objects are (X, f), where X is an algebraic variety over a finitely generated field $\mathbf{k}$ of characteristic zero and $f : X \to X$ is a dominant rational self-map defined over $\mathbf{k}$.

Contents

Chapter 1

Classifications and examples of dynamics

1.1 Examples of dynamic systems on ruled surfaces

In this section, fix an algebraically closed field $\Bbbk$ of characteristic zero.

1.1.1 Automorphism groups

The main reference is [Mar71].

$$H_r = \left\{ \left(\begin{pmatrix} \alpha & 0 \\ 0 & \alpha \end{pmatrix}, \begin{pmatrix} \alpha & t_1 \\ 0 & \alpha \end{pmatrix}, \cdots, \begin{pmatrix} \alpha & t_r \\ 0 & \alpha \end{pmatrix} \right) \in GL(2,k) \times \cdots \times GL(2,k) \;\middle|\; \begin{array}{l} \alpha \in G_m \\ t_i \in k \end{array} \right\},$$
$$H'_r = \left\{ \left(\begin{pmatrix} \alpha & 0 \\ 0 & \beta \end{pmatrix}, \begin{pmatrix} \alpha & t_1 \\ 0 & \beta \end{pmatrix}, \cdots, \begin{pmatrix} \alpha & t_r \\ 0 & \beta \end{pmatrix} \right) \in GL(2,k) \times \cdots \times GL(2,k) \;\middle|\; \begin{array}{l} \alpha, \beta \in G_m \\ t_i \in k \end{array} \right\},$$
$$\overline{H}'_r = \left\{ \left(\begin{pmatrix} \alpha & 0 \\ 0 & 1 \end{pmatrix}, \begin{pmatrix} \alpha & t_1 \\ 0 & 1 \end{pmatrix}, \cdots, \begin{pmatrix} \alpha & t_r \\ 0 & 1 \end{pmatrix} \right) \in GL(2,k) \times \cdots \times GL(2,k) \;\middle|\; \begin{array}{l} \alpha \in G_m \\ t_i \in k \end{array} \right\}.$$

Theorem 1.1.1. Let $\pi : X = \mathbb{P}_C(\mathcal{O}_C \oplus \mathcal{O}_C(-e)) \to C = \mathbb{P}^1$ be a rational ruled surface. We have an exact sequence of algebraic groups

$$1 \to \overline{H}'_{e+1} \to \mathrm{Aut}(X) \to \mathrm{PGL}(2, \Bbbk) \to 1.$$

1.1.2 Polarized induced by base

Let $\mathcal{E} = \mathcal{O}_C \oplus \mathcal{L}$ be a rank 2 vector bundle on a smooth projective curve C of genus $g \leq 1$, where $\mathcal{L}$ is a line bundle of degree $-e$ on C. Let $\pi : X = \mathbb{P}_C(\mathcal{E}) \to C$ be the associated ruled surface. Let $g : C \to C$ be an endomorphism of degree q such that $g^*\mathcal{L} \cong \mathcal{L}^q$. Fix the isomorphism $g^*\mathcal{L} \cong \mathcal{L}^q$, we have

$$g^* : \mathcal{E} \to \mathcal{O}_C \oplus \mathcal{L}^q \hookrightarrow \mathrm{Sym}^q \mathcal{E}.$$

1.2 Examples of dynamics on abelian varieties

On this section, fix an algebraically closed field $\Bbbk$ of characteristic zero. Everything is defined over $\Bbbk$ unless otherwise specified.

1.2.1 Product of elliptic curves

In this subsection, we consider the dynamics induced by matrices on the product of elliptic curves.

Let E be an elliptic curve without complex multiplication. Consider the abelian variety $X = E \times E$. Let $f_A : X \to X$ be the endomorphism defined by the matrix

$$A = \begin{pmatrix} a & b \\ c & d \end{pmatrix}.$$

Let $[F_1], [F_2], [\Delta]$ be the classes of the fibers of the two projections and the diagonal in $\mathrm{NS}(X)$. It is well-known that they span $\mathrm{NS}(X)$ and the intersection numbers are given by

$$[F_1]^2 = [F_2]^2 = [\Delta]^2 = 0, \quad [F_1] \cdot [F_2] = [F_1] \cdot [\Delta] = [F_2] \cdot [\Delta] = 1;$$

see [Laz04, Section 1.5.B].

We have that $f_A^*[F_1]$ is given by $[a]_E(x) + [b]_E(y) = 0$. Then

$$f_A^*[F_1].[F_1] = b^2, \quad f_A^*[F_1].[F_2] = a^2, \quad f_A^*[F_1].[\Delta] = (a+b)^2.$$

Hence

$$f_A^*[F_1] = (a^2 + ab)[F_1] + (b^2 + ab)[F_2] - ab[\Delta].$$

Similarly, we have

$$\begin{aligned} f_A^*[F_2] &= (c^2 + cd)[F_1] + (d^2 + cd)[F_2] - cd[\Delta], \\ f_A^*[\Delta] &= (a-c)(a+b-c-d)[F_1] + (b-d)(a+b-c-d)[F_2] - (a-c)(b-d)[\Delta]. \end{aligned}$$

Thus, the matrix representation of f_A^* on $\mathrm{NS}(X)$ with respect to the basis $\{[F_1], [F_2], [\Delta]\}$ is

$$\begin{pmatrix} a^2 + ab & c^2 + cd & (a-c)(a+b-c-d) \\ b^2 + ab & d^2 + cd & (b-d)(a+b-c-d) \\ -ab & -cd & -(a-c)(b-d) \end{pmatrix}.$$

If we take $e_1 = [F_1], e_2 = [F_2], e_3 = [\Delta] - [F_1] - [F_2]$ as a new basis of $\mathrm{NS}(X)$, then the matrix representation of f_A^* on $\mathrm{NS}(X)$ with respect to the basis $\{e_1, e_2, e_3\}$ is

$$M = \begin{pmatrix} a^2 & c^2 & -2ac \\ b^2 & d^2 & -2bd \\ -ab & -cd & ad + bc \end{pmatrix}.$$

The characteristic polynomial of M is given by

$$\chi_{f_A^*}(T) = (T - (ad - bc))(T^2 - (a^2 + d^2 + 2bc)T + (ad - bc)^2).$$

Suppose that the eigenvalues of A are λ, μ. Then the eigenvalues of f_A^* on $\mathsf{NS}(X)$ are given by $\lambda^2, \mu^2, \lambda\nu$. When $a-d, b, c$ are not all zero, $\mathsf{NS}(X)$ has two invariant subspaces of dimension 1 and 2 respectively. They are given by

$$V_1 = \mathbb{Q} \cdot \begin{pmatrix} 2c \\ -2b \\ a-d \end{pmatrix}, \quad V_2 = \mathbb{Q} \cdot \begin{pmatrix} 0 \\ a-d \\ c \end{pmatrix} \oplus \mathbb{Q} \cdot \begin{pmatrix} d-a \\ 0 \\ b \end{pmatrix} = \{(p,q,r) \mid bp - cq + (a-d)r = 0\}.$$

with respect to the basis $\{e_i\}$. One can use ?? to check this in SageMathCell.

With respect to the basis $\{e_i\}$, the cones are given by

$$\mathsf{Nef}(X) = \mathsf{Psef}(X) = \{pe_1 + qe_2 + re_3 \mid p, q \geq 0, \quad pq \geq r^2\}.$$

We analyze the intersection of V_1, V_2 with $\mathsf{Psef}(X)$. On the plane $P : p + q = 2$, fix a coordinate system (s, r) with $s = (p-q)/2 = p - 1 = 1 - q$. The cone $\mathsf{Psef}(X)$ is given by the disk $\{(s,r) \mid s^2 + r^2 \leq 1\}$. The plane V_2 is given by the equation $b(1+s) - c(1-s) + (a-d)r = (b-c) + (b+c)s + (a-d)r = 0$. If $b = c$, then the line V_1 does not intersect the plane P, hence does not intersect the interior of $\mathsf{Psef}(X)$. Otherwise, $V_1 \cap P$ is given by the point $(s,r) = \left(\frac{c+b}{c-b}, \frac{a-d}{c-b}\right)$. There are three cases:

(a) $(a+d)^2 < 4(ad-bc)$: V_1 intersects the interior of $\mathsf{Psef}(X)$, V_2 intersects $\mathsf{Psef}(X)$ at only the origin.

(b) $(a+d)^2 = 4(ad-bc)$: V_1 intersects the boundary of $\mathsf{Psef}(X)$ at a ray, V_2 intersects the boundary of $\mathsf{Psef}(X)$ at a ray.

(c) $(a+d)^2 > 4(ad-bc)$: V_1 intersects $\mathsf{Psef}(X)$ at only the origin, V_2 intersects the interior of $\mathsf{Psef}(X)$.

Note that if $b = c$, we always have $(a+d)^2 > 4(ad-bc)$ under the assumption that $a-d, b, c$ are not all zero. And note that $(a+d)^2 - 4(ad-bc) = \mathsf{disc}(\chi_A)$. Hence, we have the conclusion in table 1.1.

Case	$V_1 \cap \mathsf{Psef}(X)$	$V_2 \cap \mathsf{Psef}(X)$	dimension of minimal invariant subspace intersecting $\mathsf{Psef}(X)^\circ$
A is scalar			
A has only one eigenvalue	Boundary (ray)	Boundary (ray)	3
A has complex eigenvalues	Interior	Origin only	1
A has distinct real eigenvalues	Origin only	Interior	2

Table 1.1: Intersection of invariant subspaces V_1, V_2 with $\mathsf{Psef}(X)$ in different cases.

Now we focus on the case when A has only one eigenvalue, i.e. A is similar to a Jordan block. Assume that A is not a scalar matrix, i.e. $a-d, b, c$ are not both zero. Then easily see that $V_1 \subset V_2$ iff $(a+d)^2 = 4(ad-bc)$ iff A has the Jordan normal form $\begin{pmatrix} \lambda & 1 \\ 0 & \lambda \end{pmatrix}$ for some $\lambda \in \mathbb{Z}$. Hence in this case, there is a finite equivariant cover $(X, f) \to (X, g)$ such that g is induced by the Jordan block.

Example 1.2.1. Let $f : X \to X$ be the endomorphism defined by the matrix

$$A = \begin{pmatrix} 2 & 1 \\ 0 & 2 \end{pmatrix}.$$

Then the matrix representation of f^* on $\mathrm{NS}(X)$ with respect to the basis $\{e_1, e_2, e_3\}$ is

$$M = \begin{pmatrix} 4 & 0 & 0 \\ 1 & 4 & -4 \\ -2 & 0 & 4 \end{pmatrix}.$$

The Jordan normal form of M is

$$\begin{pmatrix} 4 & 1 & 0 \\ 0 & 4 & 1 \\ 0 & 0 & 4 \end{pmatrix}.$$

The invariant subspaces of M are given by

$$V_1 = \mathbb{R} \cdot \begin{pmatrix} 0 \\ -2 \\ 0 \end{pmatrix}, \quad V_2 = \{(p, q, r) \mid p = 0\}.$$

We have $V_2 \cap \mathrm{Psef}(X) = V_1 \cap \mathrm{Psef}(X) = \mathbb{R}_{\geq 0} \cdot (0, 1, 0)^T$. The action of f^* on $\mathrm{NS}(X)$ induces a dynamics on the plane $P : p + q = 2$; see **??**.

Chapter 2

p-adic method

2.1 Adelic topology

The main reference of this section is [Xie25].

2.1.1 Basic adelic subset

Let $\mathbf{k}$ be a finitely generated field over $\mathbb{Q}$ and $\Bbbk$ be its algebraic closure.

Let $\mathcal{J}_{\mathbf{k}}$ be the set of all embeddings $\sigma : \mathbf{k} \to \mathbb{C}_\sigma$ over $\mathbf{k}$, where $\mathbb{C}_\sigma = \mathbb{C}_p$ or $\mathbb{C}$ according to whether v is non-archimedean or archimedean. For each $\sigma \in \mathcal{J}_{\mathbf{k}}$, set $\mathcal{J}_\sigma = \{\tau : \Bbbk \to \mathbb{C}_v \mid \tau|_{\mathbf{k}} = \sigma\}$. For every $\tau \in \mathcal{J}_{\Bbbk}$, we have an induced map $\phi_\tau : X(\Bbbk) \to X(\mathbb{C}_\tau)$.

On $X(\mathbb{C}_\tau)$, we have the analytic topology induced from $\mathbb{C}_\tau$.

Definition 2.1.1. Let $\sigma, \sigma_i \in \mathcal{J}_{\mathbf{k}}$ and let $U, U_i \subseteq X(\mathbb{C}_\sigma)$ be an open subset in the analytic topology. We define

$$X_{\mathbf{k}}(\sigma, U) := \bigcup_{\tau \in \mathcal{J}_\sigma} \phi_\tau^{-1}(U) \subseteq X(\Bbbk)$$

and

$$X_{\mathbf{k}}(\{\sigma_i, U_i\}_{i=1}^n) := \bigcap_{i=1}^n X_{\mathbf{k}}(\sigma_i, U_i) \subseteq X(\Bbbk).$$

The subset of form $X_{\mathbf{k}}(\{\sigma_i, U_i\}_{i=1}^n)$ is called a *basic adelic open subset* of $X(\Bbbk)$, where $U \subseteq X(\mathbb{C}_\sigma)$ is an open subset in the analytic topology.

Theorem 2.1.2 (ref. [Xie25, Proposition 3.9] cf. [**<empty citation>**])**.** Suppose that X is irreducible. Then for any finite collection of places $\sigma_1, \ldots, \sigma_n \in M_{\mathbf{k}}$ and any basic adelic open subsets $X_{\mathbf{k}}(\sigma_i, U_i)$ for $i = 1, \ldots, n$, the intersection

$$\bigcap_{i=1}^n X_{\mathbf{k}}(\sigma_i, U_i)$$

is non-empty.

2.1.2 General adelic subset

2.1.3 Adelic topology

Yang: Is $\mathbb{A}^1(\mathbb{Q})$ adelic closed in $\mathbb{A}^1(\overline{\mathbb{Q}})$ with adelic topology? If so, why?

Yang: Describe all adelic closed subset in $\mathbb{A}^1(\overline{\mathbb{Q}})$.

2.2 Interpolation

The main reference of this section is [Ame11; BGT10; Poo14]. Let $\mathbf{k}$ be a finitely generated field over $\mathbb{Q}$ and $\Bbbk$ be its algebraic closure. Let X be a variety over $\mathbf{k}$ and $f : X \dashrightarrow X$ a dominant rational self-map defined over $\mathbf{k}$. We want to show that after iteration, we can interpolate the iterates of f on an analytic open subset of $X(\mathbb{C}_p)$ for some prime p.

2.2.1 Interpolation of analytic maps

In this subsection, we find the interpolation of analytic maps on an analytic disk. Fix a complete non-archimedean field $\mathbf{k}$ of characteristic 0 with $|p|_{\mathbf{k}} = 1/p$ for some prime p. We use the method of difference operators given in [Poo14].

Let $E = E(0,1) = \{x \in \mathbf{k}^d \mid \|x\| \leq 1\}$ be the closed unit ball in $\mathbf{k}^d$ and $\Phi : E \to E$ be an analytic map, i.e., $\Phi \in \mathbf{k}^\circ\{\underline{T}\}^d$. Here the norm on $\mathbf{k}^d$ or $\mathbf{k}^\circ\{\underline{T}\}^d$ is the supremum norm, i.e., $|x| = \max_{1\leq i\leq d} |x_i|$. For every analytic map h from E to E, we define

$$\Delta(h) := h \circ \Phi - h, \quad \Delta^n(h) := \Delta(\Delta^{n-1}(h)) \text{ for } n \geq 1,$$

and $\Delta^0(h) = h$. Note that $\Delta^n(h)$ is still an analytic map from E to E by the strong triangle inequality.

Lemma 2.2.1. We have the following binomial theorem:

$$\sum_{m=0}^{n} \binom{n}{m} \Delta^m(\mathrm{id}_E) = \Phi^n.$$

Proof. By induction, we have

$$\begin{aligned}
\Delta^m(\mathrm{id}_E) &= \Delta\left(\sum_{k=0}^{m-1} \binom{m-1}{k} (-1)^{m-1-k} \Phi^k\right) \\
&= \sum_{k=0}^{m-1} \binom{m-1}{k} (-1)^{m-1-k} \Phi^{k+1} - \sum_{k=0}^{m-1} \binom{m-1}{k} (-1)^{m-1-k} \Phi^k \\
&= \sum_{k=0}^{m} \left(\binom{m-1}{k-1} (-1)^{m-k} - \binom{m-1}{k} (-1)^{m-1-k}\right) \Phi^k \\
&= \sum_{k=0}^{m} \binom{m}{k} (-1)^{m-k} \Phi^k.
\end{aligned}$$

It follows that

$$\begin{aligned}
\sum_{m=0}^{n}\binom{n}{m}\Delta^m(\mathrm{id}_E) &= \sum_{m=0}^{n}\sum_{k=0}^{m}\binom{n}{m}\binom{m}{k}(-1)^{m-k}\Phi^k \\
&= \sum_{k=0}^{n}\sum_{m=k}^{n}\binom{n}{k}\binom{n-k}{m-k}(-1)^{m-k}\Phi^k \\
&= \sum_{k=0}^{n}\binom{n}{k}\Phi^k\sum_{l=0}^{n-k}\binom{n-k}{l}(-1)^l \\
&= \binom{n}{n}\Phi^n + \sum_{k=0}^{n-1}\binom{n}{k}\Phi^k\cdot(1-1)^{n-k} \\
&= \Phi^n.
\end{aligned}$$

We finish the proof. □

Lemma 2.2.2. Suppose that $\Phi = (\Phi_1, \cdots, \Phi_d) \in \mathbf{k}^\circ\{\underline{T}\}^d$ satisfies $\|\Phi - \mathrm{id}_E\| \le r_p$. Then Yang: To be added.

Proof. Yang: To be added. □

Theorem 2.2.3 (ref.[Poo14, Theorem 1] cf.[BGT10, Theorem 3.3])**.** Let $\mathbf{k}$ be a complete non-archimedean field of characteristic 0 with $|p|_{\mathbf{k}} = 1/p$. Set $r_p = p^{-1/(p-1)}$.
Suppose that $\Phi = (\Phi_1, \cdots, \Phi_d) \in \mathbf{k}^\circ\{\underline{T}\}^d$ satisfies $r := r_p/\|\Phi - \mathrm{id}_E\| > 1$. Then there exists a function $F \in \mathbf{k}\{\underline{T}, S/s\}^d$, $1 < s < r$, such that for each $n \in \mathbb{Z}_{\ge 0}$ and each $x \in E$,

$$F(x, n) = \Phi^n(x).$$

Proof. Consider the formal series

$$F(\underline{T}, S) := \sum_{n=0}^{\infty}\binom{S}{n}\Delta^n(\mathrm{id}_E)(\underline{T}) = \sum_{n=0}^{\infty} f_n.$$

We only need to show that $f_n \in \mathbf{k}\{\underline{T}, S/s\}^d$ and $\|f_n\| \to 0$ as $n \to \infty$.
Yang: To be added. □

Yang: If f is invertible, can we see that g is unique? Yang: It seems right.

Example 2.2.4. Let $\mathbf{k} = \mathbb{Q}_p$ with $p \ge 3$, and let $\Phi\colon E \to E$ be the analytic map defined by $\Phi(x) = px^2 + x$. Then we have $\|\Phi - \mathrm{id}_E\| = \|pT^2\| = 1/p < r_p$. Yang: To be checked.

2.2.2 Pick integral models

Lemma 2.2.5. Let $f : X \dashrightarrow X$ be a dominant rational self-map of a projective variety defined over a finitely generated field $\mathbf{k}$ over $\mathbb{Q}$.
Then there exists a subring $R \subseteq \mathbf{k}$ of finite type over $\mathbb{Z}$, a projective scheme $\mathcal{X}$ over $\operatorname{Spec} R$ with generic fiber X, and a rational self-map $\mathscr{f} : \mathcal{X} \dashrightarrow \mathcal{X}$ over $\operatorname{Spec} R$ with generic fiber f such that

(a) for every prime ideal $\mathfrak{p}$ of R, the special fiber $\mathcal{X}_{\mathfrak{p}}$ is geometrically integral and of the same dimension as X;

(b) the union of non-smooth locus of $\mathcal{X}$ and indeterminacy locus, non-étale locus of $\mathfrak{f}$ does not contain any entire special fiber $\mathcal{X}_{\mathfrak{p}}$;

Moreover, if X is smooth (resp. f is a morphism, resp. f is étale), then we can further require that $\mathcal{X}$ is smooth over $\operatorname{Spec} R$ (resp. $\mathfrak{f}$ is a morphism, resp. $\mathfrak{f}$ is étale over $\operatorname{Spec} R$).

Yang: We can embedd R into $\mathbb{C}_p$ for some p.

2.2.3 Interpolation on an analytic open subset of morphisms

The main reference of this section is [Xie25, Section 3.2]. We first state the main theorem of this section.

Theorem 2.2.6 (ref.[Xie25, Proposition 3.24])**.** Let $\mathbf{k}$ be a finitely generated field over $\mathbb{Q}$, X a projective variety defined over $\mathbf{k}$, and $f : X \dashrightarrow X$ a dominant rational self-map defined over $\mathbf{k}$.
There exists an iteration $g = f^m$ of f, an embedding $\mathbf{k} \hookrightarrow \mathbb{C}_p$ for some prime $p \geq 3$, an analytic open subset $U \subseteq X(\mathbb{C}_p)$ and an analytic map $\Phi : \mathbb{C}_p^\circ \times U \to U$ such that

(1) $U \cong (\mathbb{C}_p^\circ)^d$ analytically, where $d = \dim X$;

(2) g is well-defined on U, U is invariant under g and $\|g|_U - \mathrm{id}_U\| < 1/p$;

(3) $\Phi(n, x) = g^n(x)$ for each $n \in \mathbb{Z}_{\geq 0}$ and each $x \in U$;

Example 2.2.7. Let $X = E \times E$ with E an elliptic curve without complex multiplication defined over a number field $\mathbf{k}$, and let $f : X \to X$ be the endomorphism defined by $(a, b) \mapsto (a + b, b)$. Yang: To be continued.

2.3 Applications

2.3.1 Existence of non-preperiodic points

Theorem 2.3.1 (ref.[Ame11, Corollary 9])**.** Let $\mathbf{k}$ be an algebraically closed field of characteristic 0, X a projective variety defined over $\mathbf{k}$, and $f : X \dashrightarrow X$ a dominant rational self-map defined over $\mathbf{k}$.
Then there exists a basic adelic subset $U \subset X(\mathbf{k})$ such that the forward orbit $O_f(x) = \{f^n(x) : n \geq 0\}$ is well-defined and infinite for every $x \in U$.

2.3.2 DML conjecture for étale morphisms

Theorem 2.3.2 (ref.[BGT10, Theorem 1.3])**.** Let $\mathbf{k}$ be a field of characteristic 0, X a variety defined over $\mathbf{k}$, and $f : X \to X$ an étale morphism defined over $\mathbf{k}$. The DML conjecture holds for (X, f).

2.3.3 DML conjecture for adelic general points

References

[Ame11] E Amerik. "Existence of non-preperiodic algebraic points for a rational self-map of infinite order". In: *Mathematical Research Letters* 18.2 (2011), pp. 251–256 (cit. on pp. 6, 8).

[BGT10] Jason P Bell, Dragos Ghioca, and Thomas J Tucker. "The dynamical Mordell-Lang problem for étale maps". In: *American journal of mathematics* 132.6 (2010), pp. 1655–1675 (cit. on pp. 6–8).

[Laz04] Robert Lazarsfeld. *Positivity in algebraic geometry. I*. Vol. 48. Ergebnisse der Mathematik und ihrer Grenzgebiete. 3. Folge. A Series of Modern Surveys in Mathematics [Results in Mathematics and Related Areas. 3rd Series. A Series of Modern Surveys in Mathematics]. Classical setting: line bundles and linear series. Springer-Verlag, Berlin, 2004, pp. xviii+387. ISBN: 3-540-22533-1. DOI: 10.1007/978-3-642-18808-4. URL: https://doi.org/10.1007/978-3-642-18808-4 (cit. on p. 2).

[Mar71] Masaki Maruyama. "On automorphism groups of ruled surfaces". In: *Journal of Mathematics of Kyoto University* 11.1 (1971), pp. 89–112 (cit. on p. 1).

[Poo14] Bjorn Poonen. "p-adic interpolation of iterates". In: *Bulletin of the London Mathematical Society* 46.3 (2014), pp. 525–527 (cit. on pp. 6, 7).

[Xie25] Junyi Xie. "The existence of Zariski dense orbits for endomorphisms of projective surfaces". In: *Journal of the American Mathematical Society* 38.1 (2025), pp. 1–62 (cit. on pp. 5, 8).