BIRATIONAL MAPS WITH SPARSE POST-CRITICAL SETS

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1. A FAMILY OF BIRATIONAL MAPS

Very little is known concerning global dynamics of holomorphic maps in dimensions larger than one. Results that apply to large classes of maps (say polynomial automorphisms of $\mathbb{C}^2$ [BLS] or endomorphisms of $\mathbb{P}^n$ [BD], for example) are confined mostly to the level of ergodic theory, describing dynamics 'almost everywhere' with respect to natural invariant measures and currents. More detailed accounts exist only for specific examples. The immediate purpose of this exposition is to discuss one such example at length. Along the way I hope to also serve the broader purposes of making theorems about general maps more accessible and of indicating promising places to look for further tractable examples. All of the work described here is joint with Eric Bedford and appears in more complete form in the preprint [BD2].

We will consider the one parameter family of maps, given in affine coordinates by

$$f(x, y) = \left( \frac{x + a}{x - 1}, x + a - 1 \right).$$

(1)

One checks easily that $f$ is invertible, at least away from a couple of 'exceptional' curves along which the behavior of $f$ is either degenerate or undefined on $\mathbb{C}^2$. In fact $f$ extends as a so-called birational map to any complex surface compactifying $\mathbb{C}^2$. However, as I will explain now, it is particularly convenient to regard $f$ as a birational self-map of $\mathbb{P}^1 \times \mathbb{P}^1$.

Modulo linear equivalence $\sim$, the divisors in $\mathbb{P}^1 \times \mathbb{P}^1$ form a group (the Picard group) $\text{Pic}(\mathbb{P}^1 \times \mathbb{P}^1) \cong \mathbb{Z} \times \mathbb{Z}$ generated by a vertical line $V := [x = \text{const}]$ and a horizontal line $H := [y = \text{const}]$. Using $f$ to pull back local defining functions for divisors, we obtain a linear action $f^*$ on divisors. This action clearly preserves linear equivalence and so descends to a linear map $f^* : \text{Pic}(\mathbb{P}^1 \times \mathbb{P}^1) \cong$ on the Picard group. From the above formula, ones sees that horizontal lines pull back to vertical lines, and vertical lines pull back to hyperbolas with horizontal/vertical asymptotes. Hence with respect to the ordered basis $(V, H)$

$$f^* = \begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix}.$$  

(2)

In particular, the spectral radius of $f^*$ is the golden ratio $(1 + \sqrt{5})/2$. The dynamical relevance of this quantity is revealed by the following result due essentially to Gromov (see Dinh and Sibony [DS] for the most general version to date).

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Theorem 1.1. Let $f : X \to X$ be a birational map on a complex projective surface $X$. Then the topological entropy $h_{\text{top}}(f)$ of $f$ satisfies

$$h_{\text{top}}(f) \leq \lim_{n \to \infty} \frac{\log \|(f^n)^*\|}{n}.$$ 

In addition, Dujardin [Duj] has recently shown that this inequality is actually an equality for a large class of birational maps (including those in (1)). So for $f$ given by (1) we have

$$h_{\text{top}}(f) = \log \frac{1 + \sqrt{5}}{2}$$

provided that

$$(f^n)^* = (f^*)^n$$

for all $n \in \mathbb{N}$. (3)

This latter identity can fail dramatically in general, but we will see shortly that it holds for the family (1) for all but countably many values of the parameter $a$. Forness and Sibony call maps satisfying (3) algebraically stable.

It should perhaps be stressed that (3) is a property of both the map and the choice of compactification of $\mathbb{C}^2$. For example, if $I$ were treating $f$ as a self-map of $\mathbb{P}^2$, then the Picard group acted on by $f^*$ would be one-dimensional, generated by a generic line in $\mathbb{P}^2$, and $f^*$ would simply double this generator. However, $(f^2)^*$ would multiply by 3 (check this!) rather than $2^2 = 4$. Thus the surface $\mathbb{P}^1 \times \mathbb{P}^1$ is 'compatible' with the map $f$ in a way that $\mathbb{P}^2$ is not.

To better understand the situation, let us reconsider things from a geometric point of view. On $\mathbb{P}^1 \times \mathbb{P}^1$, the critical set $\mathcal{C}(f)$ of $f$ is the pair of lines $\{x = -a\} \cup \{x = 1\}$. As is the case for birational maps generally, the components of $\mathcal{C}(f)$ are critical because they are exceptional: each is mapped to a single point: $\{x = -a\}$ to $(0, -1)$ and $\{x = 1\}$ to $(\infty, a)$. Consequently, the inverse map

$$f^{-1}(x, y) = (y - a + 1, x \frac{y - a}{a + 1})$$

cannot be defined continuously at either image point, a fact which one can verify directly from the formula for $f^{-1}$. The set $I(f^{-1}) := \{(0, -1), (\infty, a)\}$ is called the indeterminacy set of $f^{-1}$. Similar analysis reveals that

$$\mathcal{C}(f^{-1}) = \{y = -1\} \cup \{y = a\} \quad I(f) = \{(-a, \infty), (1, 0)\}.$$ 

If we change our compactification of $\mathbb{C}^2$, the sets $\mathcal{C}(f^\pm)$ and $I(f^\pm)$ are all prone to change as well. It turns out (in general) that (3) is equivalent to

$$f^n\mathcal{C}(f) \cap f^{-m}\mathcal{C}(f) = \emptyset$$

for all $n, m > 0$ (4)

In other words $f$ satisfies (3) if and only if 'postcritical' orbits

$$\mathcal{P}C(f) := \bigcup_{n > 0} f^n\mathcal{C}(f), \quad \mathcal{P}C(f^{-1}) \bigcup_{m > 0} f^{-m}\mathcal{C}(f^{-1})$$

avoid each other.

The condition (4) has a deceptively simple appearance. For general maps, it can be quite difficult to verify, because it requires knowing about the full orbit of each

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1When $V$ is a curve that meets $I(f)$, we define $f(V)$ to be the set $f(V \setminus I(f))$. In other words, $f(V)$ is the proper transform of $V$ and excludes all components of $\mathcal{C}(f^{-1})$. This notion of $f(V)$ does not entirely accord with that of $f_*V := (f^{-1})^*V$: in general $f(V) \subset \text{supp} f_*V$, but the inclusion will be proper when $V \cap I(f) \neq \emptyset$. To take a concrete example, we have $f(\{(x = a)\}) = (0, 1)$, whereas $f_*\{x = -a\} = \{y = 1\}$ includes the 'image' of the point $(-a, \infty) \in I(f)$. 

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component of $C(f)$. Things are easier, however, for the example at hand. Our map $f$ has the additional virtue that it preserves a meromorphic two form:

$$f^* \eta = f_* \eta = \eta := \frac{dx \wedge dy}{y - x + 1}.$$ 

It follows more or less immediately that the support of the divisor $[\eta] = [x = \infty] + [y = \infty] + [y = x - 1]$
of $\eta$ is invariant under $f$. Direct computation with parametrizations reveals more
specifically that $\{y = x - 1\}$ is fixed and the lines at infinity are switched according to

$$(x, x - 1) \mapsto (x + a, x + a - 1) \quad (\infty, y) \mapsto (\infty, y + a - 1).$$

In particular, the point $(\infty, \infty)$ is fixed by $f$.

Invariance of $\eta$ also implies that critical components of $f$ must map into $\text{supp} [\eta]$.
Hence $\mathcal{P} C(f), \mathcal{P} C(f^{-1}) \subset \text{supp} [\eta]$, and the happy consequence is that we can
determine whether or not $f$ satisfies (4) by restricting our attention to the completely
tractable one dimensional dynamics of $f$ on $\text{supp} [\eta]$.

2. Real dynamics for negative parameters

Though we could easily, in light of the preceding discussion, identify all parameters $a$ for which (4) fails, let us attend only to the case $a < 0$. The parameter $a = -1$ is special, because the first coordinate of $f$ degenerates, the critical and
indeterminacy sets disappear, and the map dynamics become trivial. For all other
$a < 0$, (4) holds in a particularly robust fashion. For example $\mathcal{P} C(f) \cap \{y = x - 1\}$ is just the forward orbit of the point $(-1, 0)$. If we let

$$S := \{(x, x - 1) : x \leq 0\}$$

be the real interval in $\{y = x - 1\}$ that stretches from $(-1, 0)$ down and left to
$(\infty, \infty)$, then we see that $f(S) \subset S$ when $a < 0$. Therefore $\mathcal{P} C(f) \cap \{y = x - 1\} \subset S$.
Likewise, the interval

$$U := \{(x, x - 1) : x \geq 1\}$$
stretching from $(1, 0)$ up and right to $(\infty, \infty)$ satisfies $f^{-1}(U) \subset U$ when $a < 0$ and
therefore contains $\mathcal{P} C(f^{-1}) \cap \{y = x - 1\}$. As $U$ and $S$ are disjoint, it follows that $\mathcal{P} C(f) \cap \mathcal{P} C(f^{-1})$ contains no points in $\{y = x - 1\}$.

Similar observations apply to the lines $\{x = \infty\}$ and $\{y = \infty\}$. When $a < 0$,
each line contains disjoint, forward/backward invariant, real intervals $S$ and $U$ that
separating $\mathcal{P} C(f)$ from $\mathcal{P} C(f^{-1})$, and it follows that $\mathcal{P} C(f) \cap \mathcal{P} C(f^{-1})$ is empty.

Figure 1 summarizes this state of affairs for $a < -1$. The real points in $\mathbb{P}^1 \times \mathbb{P}^1$ form a torus. Removing $\text{supp} [\eta]$ divides the remaining real points into two open
sets, labeled 0 and 1. The boundary of each open set is exactly equal to the real
points in $\text{supp} [\eta]$. $S(\text{table})$ and $U(\text{nstable})$ segments in each boundary component
are thickened for emphasis. Finally, the critical and indeterminacy sets of $f$ and $f^{-1}$
are included for the sake of completeness. The picture remains valid for parameter
values $-1 < a < 0$, except that the critical lines for $f$ (and for $f^{-1}$) switch places.

Let us regard two stable segments that are adjacent in the boundary of region
0 or 1 as part of a single larger boundary segment. In this way, the boundaries of
regions 0 and 1 may be regarded as 'rectangles', each with opposing pairs of stable
and unstable 'sides'. This suggests that for real parameters $a$, we try to use the
two regions as a Markov partition for the dynamics of f. Let \( \Sigma \) be the space of bi-infinite sequences \( \{0, 1\}^\mathbb{Z} \) (with the product topology) and

\[
D := \{ p \in \mathbb{R}^2 : f^n(p) \notin \text{supp}[\eta] \text{ for all } n \in \mathbb{Z} \} = \mathbb{R}^2 - \text{supp}[\eta] - \bigcup_{n \in \mathbb{Z}} C(f^n)
\]

consist of those points whose orbits lie entirely in the interior of regions 0 and 1. Define a map

\[
w : D \to \Sigma, \quad p \mapsto \ldots \ w_{-1} w_0 \cdot w_1 w_2 \ldots,
\]

where \( w_j \in \{0, 1\} \) records the region that contains \( f^j(p) \). It is not hard to see that \( w \) is continuous. Moreover, if \( \sigma : \Sigma \circlearrowleft \) is the shift homeomorphism

\[
\ldots w_{-1} w_0 \cdot w_1 w_2 \ldots \overset{\sigma}{\mapsto} \ldots w_{-1} w_0 w_1 \cdot w_2 \ldots,
\]

then we clearly have a commutative diagram

\[
\begin{array}{ccc}
D & \xrightarrow{f} & D \\
\downarrow w & & \downarrow w \\
\Sigma & \xrightarrow{\sigma} & \Sigma
\end{array}
\]
More importantly and much less obviously, we can say a great deal about the fiber of $w$ over any point in $\Sigma$. Consider the following subsets of $D$.

\[
D_+ = \{ p \in D : \lim_{n \to \infty} f^n p = (\infty, \infty) \} \\
D_- = \{ p \in D : \lim_{n \to \infty} f^{-n} p = (\infty, \infty) \} \\
\Omega = D - D_+ - D_-
\]

Let us call the coding $w(p)$ of $p \in D$ forward alternating if some righthand tail $w_jw_{j+1}w_{j+2} \ldots$ of $w(p)$ has the form 0101. . . . Let us call $w(p)$ backward alternating if some lefthand tail . . . $w_{j-2}w_{j-1}w_{j}$ has the analogous property. Let $\Sigma_G \subset \Sigma$ denote the (closed) subset consisting of all sequences without consecutive 1's. The main result of this exposition is

**Theorem 2.1.** Suppose that $a < 0$, $a \neq -1$. Let $p \in D$ be any point. Then

- $p \in D_+$ if and only if $w(p)$ is forward alternating.
- $p \in D_-$ if and only if $w(p)$ is backward alternating.

Finally, $w : \Omega \to \Sigma$ is a homeomorphism onto those sequences in $\Sigma_G$ that are neither forward nor backward alternating.

Since the dynamics of $f$ on $\text{supp} [\eta]$ are trivial, Theorem 2.1 gives a rather precise topological description of the real dynamics of $f$. I will quickly indicate two consequences of this theorem and then discuss some ingredients of the proof.

**Corollary 2.2.** $\Omega$ consists exactly of those points in $D$ with recurrent orbits.

The entropy of a restricted map never exceeds that of the map itself, so on this general principle we know that

\[
h_{top}(f : \Omega \circ) \leq h_{top}(f : \overline{\mathbb{R}}^2 \circ) \leq h_{top}(f : \mathbb{P}^1 \times \mathbb{P}^1 \circ) = \frac{1 + \sqrt{5}}{2}.
\]

On the other hand, the shift map $\sigma$ restricts to a well-defined homeomorphism of $\Sigma_G$ whose entropy is well-known to be $\log \frac{1 + \sqrt{5}}{2}$. Since removing the relatively small sets of forward/backward alternating codings does not alter the value of the entropy, we can conclude that

**Corollary 2.3.** For all $a < 0$, $a \neq -1$, the topological entropy of $f$ as a real map is $\log \frac{1 + \sqrt{5}}{2}$.

The fundamental idea underlying Theorem 2.1 is that forward and backward images of real arcs may be studied in two different ways: from a combinatorial point of view based on Figure 1, and from the more abstract perspective of complex intersection theory. I discuss these points of view in order.

3. Combinatorics

From now on I will assume that $a < -1$. I call a real arc 'stable' if it is completely contained in one of the two regions in Figure 1, and it joins the two unstable segments in the boundary of that region. To justify this definition, let me consider for example the preimage $f^{-1}(\gamma)$ of a stable arc $\gamma$ in region 0. Say for specificity's sake that $\gamma$ joins the unstable segment in $\{ y = x - 1 \}$ to the unstable segment in $\{ y = \infty \}$. Then $\gamma$ necessarily crosses both lines in $\mathcal{C}(f^{-1})$, and the preimage $f^{-1}(\gamma)$ must therefore contain three subarcs: one joining the unstable segment in $\{ y = x - 1 \} = f^{-1}(y = x - 1)$ to $(\infty, -a) = f^{-1}(y = -1)$, one joining $(\infty, -a)$
to $(1,0) = f^{-1}\{y = \alpha\}$, and one joining $(0,-1)$ to the unstable segment in \( \{x = \infty\} = f^{-1}\{y = \infty\} \). By checking the images of points in \( \gamma \) near \( \supp[\eta] \cup \mathcal{C}(f^{-1}) \), one sees that the first and third arcs lie in region 0, whereas the second lies in region 1. In particular the second third subarcs join opposing unstable segments in regions 0 and 1, respectively, and are therefore themselves stable (the first subarc is not stable since both of its endpoints lie in the same unstable segment in region 0). Repeating this argument proves that the preimage \( f^{-1}(\gamma) \) of an stable arc \( \gamma \) in region 1 must contain an stable arc in region 0. After induction we arrive at

**Theorem 3.1.** Let \( m \geq 0 \) and \( w_0 \cdot w_1 \ldots w_m \) be a finite righthand sequence of 0's and 1's without consecutive 1's. Let \( \alpha \) be a stable arc in region \( w_m \). Then \( f^{-m}(\alpha) \) contains a stable arc \( \gamma \) in region \( w_0 \) such that \( f^j(\gamma) \) lies in region \( w_j \) for \( j = 0, \ldots, m \).

Of course, we can also define 'unstable' arcs in regions 0 and 1, and proceed in exactly the same fashion to prove

**Theorem 3.2.** Let \( n \geq 0 \) and \( w_{-n} \ldots w_0 \cdot w_1 \ldots w_m \) be a finite lefthand sequence of 0's and 1's without consecutive 1's. Let \( \beta \) be an unstable arc in region \( w_{-n} \). Then \( f^n(\beta) \) contains an unstable arc \( \gamma \) in region \( w_0 \) such that \( f^{-j}(\gamma) \) lies in region \( w_j \) for \( j = 0, \ldots, n \).

The fact that stable and unstable boundary segments of regions 0 and 1 are disjoint implies that any stable arc in a given region intersects any unstable arc from the same region. So Theorems 3.2 and 3.1 give us a convenient way to produce points with orbits coded by finite two-sided sequences of any extent.

**Corollary 3.3.** Let \( n, m \geq 0 \) and \( w_{-n} \ldots w_0 \cdot w_1 \ldots w_m \) be any finite sequence of 0's and 1's without consecutive 1's. Then there is a point \( p \in D \) such that \( c(p) = \ldots w_{-n} \ldots w_0 \cdot w_1 \ldots w_m \ldots \)

It is not quite immediate (and not quite true!) that the image \( w(D) \) of the coding map contains \( \Sigma_G \), let alone that the assertions of Theorem 2.1 concerning \( w|_\eta \) are true. However, Corollary 3.3 is clearly a step in the right direction. Further progress depends on refining the partition shown in Figure 1.

For any \( n \geq 0 \), every component in the critical set \( \mathcal{C}(f^n) \) maps, eventually, into the stable portion of \( \supp[\eta] \). So we can subdivide our original partition using \( \mathcal{C}(f^n) \) for any \( n \in \mathbb{N} \), designating all the new boundary components 'stable'. Similarly, we can subdivide by \( \mathcal{C}(f^{-n}) \), designating all inverse critical components 'unstable'. And while it is not strictly necessary, we can try to simplify the picture that results by recombining some of the new partition pieces, provided we take care to preserve invariance of stable/unstable boundary components. The result of this process, obtained with care and hindsight, is shown in Figure 2. The original regions 0 and 1 become smaller rectangles \( R_0 \) and \( R_1 \), and the complement of \( R_0 \cup R_1 \) decomposes into overlapping regions labeled \( R_+ \) and \( R_- \). Using only combinatorial arguments like the ones above, the following can be established.

**Proposition 3.4.** The conclusion of Corollary 3.3 holds with the regions 0 and 1 from Figure 1 replaced by regions \( R_0 \) and \( R_1 \) from Figure 2. Moreover,

- \( f(R^+) \subset R^+ \), and any point \( p \in R^+ \cap D \) has a forward coding \( w_0 \cdot w_1 \ldots \) that alternates and a forward orbit that tends to \( (\infty, \infty) \).
- \( f^{-1}(R^-) \subset R^- \), and any point \( p \in R^- \cap D \) has a backward coding \( \ldots w_1 w_0 \cdot \) that alternates and a backward orbit that tends to \( (\infty, \infty) \).
FIGURE 2. Refinement of the original partition to include critical curves. Stable and unstable boundary segments are labeled 's' and 'u', respectively.

- $f(R_1) \cap R_1 = \emptyset$.

Together with the following, somewhat technically difficult result; Corollary 3.3 and Proposition 3.4 combine to imply everything in Theorem 2.1 except the injectivity of $f|\Omega$.

**Proposition 3.5.** Any point $p \in D$ such that $\lim_{n \to \infty} f^n(p) = (\infty, \infty)$ (respectively, $\lim_{n \to -\infty} f^{-n}(p) = (\infty, \infty)$) must satisfy $f^n(p) \notin R^0 \cup R^1$ (respectively, $f^{-n}(p) \notin R^0 \cup R^1$) for arbitrarily large $n \in \mathbb{N}$.

4. INTERSECTION THEORY

Here is a slightly different and less precise way to state Corollary 3.3. Suppose we are given $i,j \in \{0,1\}$, a stable arc $\alpha$ in region $i$, an unstable arc $\beta$ in region $j$, and $m,n \in \mathbb{N}$. Then $f^{-m}(\alpha) \cap f^n(\beta)$ must contain at least

$$\left\langle \begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix} e_i, \begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix} e_j \right\rangle$$

(5)

distinct points in $R_0 \cup R_1$. Equation (5), in which $e_0,e_1$ are the standard basis vectors for $\mathbb{R}^2$, simply counts the number of codings $w_{-n} \ldots w_0 \cdot w_1 \ldots w_m$ that begin with digit $w_{-n} = i$, end with digit $w_m = j$, and contain no consecutive 1's throughout. The combinatorial arguments sketched above do not rule out the
possibility that there might be more intersections than (5) provides. To obtain
two turns from above, I change tactics and consider only very special examples of
stable and unstable curves.
Namely, I suppose that $\alpha$ is obtained by intersecting $R_0$ with a vertical line or
$R_1$ by the preimage of a vertical line, and that $\beta$ is obtained similarly. This turns
out not to be too severe since both regions have a product structure given by stable
and unstable curves of this sort. The advantage to the restriction is that complex
intersection theory tells us exactly how many times one algebraic curve intersects
another and therefore gives us an upper bound on $\# f^{-m}(\alpha) \cap f^n(\beta)$. The data
needed to obtain this upper bound are the basis $(V, H)$ for Pic $(P^1 \times P^1)$, the matrix
(2) for $f^*$ with respect to this basis, and additionally, the matrix

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

for the intersection form for complex curves in $P^1 \times P^1$. The results take a bit of
interpreting because the algebraic curves giving the stable and unstable foliations
of $R_1$ also intersect $R_0$ is stable and unstable arcs. However, in the end we obtain
an upper bound for $\# f^{-m}(\alpha) \cap f^n(\beta)$ that matches (5) exactly in all cases. In
light of (2), we might have expected close agreement even before setting pencil
to paper, but exact agreement is not a priori obvious (at least not to me). It is
fortunate, though, because precise agreement between upper and lower bounds is
the main thing needed to complete the proof of Theorem 2.1 (i.e. of injectivity of
$f: \Omega \to \Sigma_G$.)

Rather than go into more detail here, I will describe some further consequences
of intersection theory for dynamics of $f$. By using Lefschetz' theorem on periodic
points, it can be shown that

**Theorem 4.1.** All periodic points of $f$ are real. Indeed all except $(\infty, \infty)$ are
saddle points contained in $\Omega$, and saddle periodic points constitute a dense subset
of $\Omega$.

So far, I have mostly described the set $\Omega = D - D_- - D_+$ of points whose orbits
lie neither the forward nor the backward basin of $(\infty, \infty)$, but in fact the individual
complements of $\Omega_+ := D - D_+$ and $\Omega_- := D - D_-$ yield to the same analysis.

**Theorem 4.2.** $\Omega_+$ is the support of a geometric 1 current $\mu^+$. That is, there is a
lamination $\mathcal{L}^+$ in $P^1 \times P^1 - \text{supp } [\eta]$ and a measure $\nu^+$ on the set $|\mathcal{L}|^+$ of leaves
of this laminating such that

- $\mu^+(\zeta) = \int_{|\mathcal{L}|^+} (\int_L \zeta) \nu^+(L)$ for all 1 forms $\zeta$;
- $\text{supp } \mathcal{L}^+ = \Omega_+$;
- Every leaf of $\mathcal{L}^+$ is a stable curve in regions 0 or 1 from Figure 1;
- $\nu^+$ is invariant under holonomy along $\mathcal{L}^+$;
- $f^* \mu^+ = -\mu^+$.

Note that I am avoiding the matter of orientation in the first and last items. Figure
4 shows $\mathcal{L}^+$ by itself and together with the corresponding lamination $\mathcal{L}^-$ comple-
menting $D_-$. The common intersection of the two laminations is just (the closure
of) $\Omega$. 
Complex intersection theory can be used to study dynamics of any rational map. Indeed the currents $\mu^+$ and $\mu^-$ have general complex analogues for any dynamically interesting birational map, and the intersection between $\mu^+$ and $\mu^-$ can often be understood in at least a measure theoretic sense (see [BD1]). What is special to the example I have just described is the presence of a good combinatorial structure. In my view, there are two key features of the example from which the combinatorics proceed. First of all, the post-critical orbits $\mathcal{PC}(f)$ and $\mathcal{PC}(f^{-1})$ lie in invariant curves and are therefore very easy to understand. Second, rather than being interlaced in some complicated fashion, the sets $\mathcal{PC}(f)$ and $\mathcal{PC}(f^{-1})$ are easily separated by dividing each real invariant curve into a pair of intervals. Some of the other aspects of the example, such as the perfect agreement between intersection theory and combinatorics, remain mysterious to me. In a forthcoming paper, Bedford and I will describe another family of birational maps whose real dynamics can be analyzed in a similar fashion. It does not seem too hard to come by further families of maps with “sparse postcritical sets” so it is interesting to wonder how far the analysis described here can be extended.

REFERENCES


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