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Jerome Buzzi. Puzzles of Quasi-Finite Type, Zeta Functions and Symbolic Dynamics for Multi-Dimensional Maps. 2006. hal-00110435v1

**HAL Id: hal-00110435**

**<https://hal.science/hal-00110435v1>**

Preprint submitted on 29 Oct 2006 (v1), last revised 14 Sep 2009 (v2)

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**PUZZLES OF QUASI-FINITE TYPE, ZETA FUNCTIONS AND  
SYMBOLIC DYNAMICS FOR MULTI-DIMENSIONAL MAPS**

JÉRÔME BUZZI

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## 1. INTRODUCTION

In what sense(s) can a dynamical system be “complex” and what is the interplay between this complexity and the more classical dynamical properties? A very large body of works has been devoted to this basic question, especially to prove various forms of complexity from dynamical assumptions. We are interested in reversing this direction:

*What are the dynamical consequences of complexity?  
Can complexity characterize a dynamical system?*

This type of question has been studied mainly in low-complexity settings (see, e.g., [1] and the references therein). We have shown, first in a smooth setting, that a **high-complexity** assumption (which we called *entropy-expansion*) also has very thorough dynamical implications [6]. A remarkable feature is that this condition, which involves only so-called dimensional entropies, is enough to analyze measures of maximum entropy and the related periodic points. We are even able to classify such systems with respect to all their ergodic and invariant measures of high entropy. Thus complexity can be analyzed using only (simple) complexity assumptions.

However the proofs in [6] mix both combinatorial/entropic arguments and geometric ones involving Lyapunov exponents, the smoothness and the ensuing approximations by polynomials, raising the question of separating completely both issues. This separation has been achieved in [8] for, e.g., subshifts of finite type and piecewise monotonic interval maps with nonzero entropy, giving a common proof to their common “complexity” properties. However the required estimates could not be proved for higher dimensional maps satisfying the entropy-expansion condition mentioned above.

The present paper fills this gap by introducing a suitable type of *symbolic dynamics* which we call **puzzles of quasi-finite type** –these are puzzles in the sense of Yoccoz’ construction in complex dynamics. In comparison with our work in [6] we have to make an additional, probably generic, assumption, but we also obtain more detailed information about the periodic points.

The puzzle of quasi-finite type are the generalization of the subshifts of quasi-finite type [8] needed for multi-dimensional, non-linear maps. We generalize to these puzzles all the results obtained for subshifts:

- existence of a finite number of ergodic probability measures maximizing the entropy;

- meromorphic extension of (suitably defined) Artin-Masur zeta functions counting the periodic points;
- equidistribution of the periodic points;
- classification with respect to measure of large entropy.

We in fact obtain a *larger meromorphic extension* of the zeta function than in our paper [8]. It is proved using a new result (Theorem 4) relating the radius of meromorphy of some zeta functions of Markov shifts to their entropy at infinity (see Definition 1.9). This is of independent interest.

**1.1. Definitions.** We recall the notion of a puzzle due to Yoccoz [24] (closely related are the *tableaux* of Branner and Hubbard).

**Definition 1.1.** A **puzzle** is  $(V, i, f)$  (or just  $V$ ), a set of pieces  $V = \sqcup_{n \geq 0} V_n$  (a disjoint union of finite sets) and two maps  $i, f : V \setminus V_0 \rightarrow V$  satisfying:

- $V_0$  has a single element;
- $i \circ f = f \circ i$ ;
- $i(V_{n+1}) \subset V_n$ ;
- $f(V_{n+1}) \subset V_n$ .

The order of a piece  $v$  is  $|v|$ , the unique integer  $n$  such that  $v \in V_n$ .

**Definition 1.2.** A puzzle  $(V, i, f)$  defines the following zero-dimensional dynamics  $F_V : X_V \rightarrow X_V$ :

$$X_V = \{v \in V_0 \times V_1 \times \cdots : \forall n \geq 0 \ i(v_{n+1}) = v_n\}$$

$$F_V : (v_n)_{n \geq 0} \mapsto (f(v_{n+1}))_{n \geq 0}.$$

This dynamics can be, up to a topological conjugacy, *any* continuous self-map  $F$  of a Cantor set  $K$ , i.e., for each such  $F : K \rightarrow K$ , there exist a puzzle  $V$  and a homeomorphism  $\phi : X_V \rightarrow K$  with  $\phi \circ F_V = F \circ \phi$  (see Section 2.2). To get a tractable class one has to make some assumptions. Ours will say that the puzzle is simple in the sense that it is defined by "not too many constraints". Let us give the definitions.

*A notion of constraint: irreducibility.* Let the  $i$ -tree below  $v \in V$  be the directed graph  $\mathcal{T}_i(v)$  whose vertices are the  $w \in V$  such that  $i^n(w) = v$  for some  $n \geq 0$  and whose edges are  $u \rightarrow u'$  iff  $u' = i(u)$ .

**Definition 1.3.** A piece  $v \in V \setminus V_0$  is  **$f$ -reducible** if the two following conditions hold:

- (R1)  $f : \mathcal{T}_i(v) \rightarrow \mathcal{T}_i(f(v))$  is a graph isomorphism;
- (R2) there is no  $w \neq v$  such that  $i(w) = i(v)$ ,  $f(w) = f(v)$  and (R1) holds also for  $w$ .

Otherwise,  $v$  is said to be  $f$ -irreducible.

**Notations.**  $v \succeq_f^1 w$  means that  $v$  is  $f$ -reducible and  $w = f(v)$ . For  $k > 1$ ,  $v \succeq_f^k w$  is defined inductively as  $v \succeq_f^1 f(v)$  and  $f(v) \succeq_f^{k-1} w$  (by convention  $v \succeq_f^0 v$  for any  $v \in V$ ). Finally  $u \succeq_f w$  means that  $u \succeq_f^k w$  for some  $k \geq 1$ .

*Remark.* Property (R1) was introduced by Yoccoz under the name of "regularity". It is equivalent to the following dynamical property (here  $[v]_V := \{x \in X_V : x_{|v|} = v\}$ ):

$$F_V : [v]_V \rightarrow [f(v)]_V \text{ is a bijection}$$

Condition (R2) seems new. It is often a consequence of (R1) –this is the case, if, for instance, the restrictions  $F_V|_{[v]_V}$ ,  $v \in V$ , are one-to-one.

*Remark.* In the case where the puzzle is given by a subshift as in section 2.1, condition (R2) of Definition 1.3 is automatically satisfied (indeed,  $f(v) = f(w)$  and  $i(v) = i(w)$  imply  $v = w$ ) and condition (R1) is equivalent to the notion of minimum left constraint introduced for subshifts of quasi-finite type in [8].

One can understand the  $f$ -irreducible pieces as describing the constraints in  $X_V$ .  $v$   $f$ -reducible implies that the possible  $i$ -extensions of  $v$  are the same as those of  $f(v)$ . This is a sort of "local Markov property". For instance, if all pieces are reducible then  $X_V = V_1^{\mathbb{N}}$ . A slightly less extreme example of this phenomenon is:

**Lemma 1.4.** *If a puzzle  $V$  has only finitely many  $f$ -irreducible vertices, then  $X_V$  is (topologically conjugate to) a subshift of finite type, i.e., a subshift of  $\{1, 2, \dots, d\}^{\mathbb{N}}$  for some  $d \geq 1$ , obtained by excluding a finite number of finite sequences [34].*

More generally, one can expect puzzles with few  $f$ -irreducible vertices to be "simple". The definition below formalizes this idea.

*Entropy on the puzzle.* The puzzle  $V$  will be equipped with the following *combinatorial distance*: for  $v \neq w$ :

$$d_V(v, w) = 2^{-n} \quad \text{if } n = \max\{0 \leq k \leq \min(|v|, |w|) : i^{|v|-k}(v) = i^{|w|-k}(w)\}$$

Note:  $d_V(v, w) \leq d_V(i(v), i(w)) \leq 2d_V(v, w)$ , the first inequality being an equality except when  $v = i^{|w|-|v|}(w)$  or  $w = i^{|v|-|w|}(v)$ .  $d_V(f(v), f(w)) \leq 2d_V(v, w)$ .

The corresponding metric on  $X_V$  is

$$d_V(x, y) := \sup_{n \geq 0} d_V(x_n, y_n) = 2^{-n} \text{ such that } n = \min\{k \geq 0 : x_k \neq y_k\} \text{ or } \infty.$$

Together with  $f$ , this induces a notion of Bowen balls in  $V$ : For  $v \in V$ ,  $\epsilon > 0$ ,  $n \in \mathbb{N}$ , the  $(\epsilon, n)$ -ball around  $v$  is:

$$B(v, \epsilon, n) := \{w \in V : \forall 0 \leq k < \min(n, |v|, |w|) \ d_V(f^k w, f^k v) < \epsilon\}$$

The covering numbers  $r(\epsilon, n, S)$  are again the minimum number of  $(\epsilon, n)$ -balls needed to cover  $S \subset V$ . We define the **topological entropy of a sequence**  $\mathcal{S}$  of subsets  $S_n \subset V_n$ ,  $n \geq 1$ , as:

$$h_{\text{top}}(\mathcal{S}) = \lim_{\epsilon \rightarrow 0} \limsup_{n \rightarrow \infty} \frac{1}{n} \log r(\epsilon, n, S_n).$$

We recall first Bowen's formula for topological entropy. The  $(\epsilon, n)$ -Bowen ball at  $x$  w.r.t.  $F_V$  (and a distance  $d$  on  $X_V$ ), is  $B(x, \epsilon, n) := \{y \in X_V : \forall k < n \ d(F_V^k x, F_V^k y) < \epsilon\}$ . The *topological entropy* [34] is

$$h_{\text{top}}(F_V) := \lim_{\epsilon \rightarrow 0} h_{\text{top}}(F_V, \epsilon) \text{ with } h_{\text{top}}(F_V, \epsilon) = \lim_{\delta \rightarrow 0} \limsup_{n \rightarrow \infty} \frac{1}{n} \log r(\epsilon, n, X_V)$$

where  $r(\epsilon, n, S)$  is the minimum number of  $(\epsilon, n)$ -balls necessary to cover  $S$ . We sometimes write  $h_{\text{top}}(V)$  instead of  $h_{\text{top}}(F_V)$ .

*Constraint entropy.* We now state our main condition on the complexity of puzzles

**Definition 1.5.** *The constraint entropy of a puzzle  $V = (V, i, f)$  is:*

$$h_C(V) := h_{\text{top}}((C_n)_{n \geq 1})$$

where  $C_n$  is the set of irreducible pieces of order  $n$ .

The puzzle  $V$  is of **\*-quasi-finite type** (or, for short, **\*-QFT**) if it satisfies:

$$h_C(V) < h_{\text{top}}(V)$$

This notion is essentially unrelated to that of subshifts of subshifts of weakly quasi-finite type defined in [8].

*W-Local entropy.* \*-QFT puzzles can still present complexity at arbitrarily small scales. For example one can build \*-QFT puzzles which are the union of sequences of subshifts of finite type with equal or increasing entropy so that they have either infinitely many or no ergodic invariant probability of maximum entropy (for short, **maximum measures**) —see section 2.4.

Our second restriction prevents these phenomena.

**Definition 1.6.**  *$V$  being a \*-QFT puzzle, the W-local entropy of  $V$  is the defect in uniformity of  $h(F_V, \mu) = \lim_{\epsilon \rightarrow 0} h(F_V, \mu, \epsilon)$  over large entropy measures (that is, ergodic invariant probability measures with entropy close to the supremum):*

$$h_{\text{wloc}}(V) := \inf_{\epsilon > 0} \sup_{\mu} h(F_V, \mu) - h(F_V, \mu, \epsilon)$$

where  $\mu$  ranges over the ergodic invariant probability measures on  $X_V$  with entropy  $> h_C(V)$ .

*Remark.*

(1) Obviously,  $h_{\text{wloc}}(V) \leq h_{\text{loc}}(F_V)$ , the *local entropy* (introduced by Misiurewicz [27] under the name topological conditional entropy) which indeed bounds this defect in uniformity over *all* measures. In particular,  $h_{\text{wloc}}(V) = 0$  if  $F_V$  is expansive, e.g., a subshift.

(2) It might also be interesting to consider  $h_{\text{exp}}(T)$ , the infimum of the numbers  $h > 0$  such that there exists  $\epsilon > 0$  satisfying: for all ergodic and invariant probability measure  $\mu$  with  $h(T, \mu) > h$ ,  $h(T, \mu) = h(T, \mu, \epsilon)$ . It could be called *expansiveness entropy* (not related to entropy-expansion). See also [28] and the references therein for some relations between various (robust) expansiveness and hyperbolic properties.

(3) Observe that if  $\delta_{\text{usc}}(T)$  is the defect in uppersemicontinuity of the entropy function over the set of invariant probability measures of  $T$ , then

$$h_{\text{top}}(T) > h_{\text{exp}}(T) + \delta_{\text{usc}}(T)$$

is, trivially, a sufficient condition for the existence of a measure of maximum entropy. This condition could be helpful notably for  $C^r$  interval maps where there remains a gap between the known sufficient lower bound on entropy [9] and that in the counter-examples [3, 29].

**Definition 1.7.** *A QFT puzzle (or just QFT) is a puzzle  $(V, i, f)$  which satisfies:*

$$h_C(V) + h_{\text{wloc}}(V) < h_{\text{top}}(V).$$

The notions of QFT and \*-QFT puzzles can be readily generalized in the following fashion (adding new examples —as this already happens for subshifts, see [8]). Observe that if  $(V, i, f)$  is a puzzle, then so is:  $(V^*, i^*, f^*)$  with  $V^* = V$ ,  $i^* = f$  and  $f^* = i$ .  $(V^*, i^*, f^*)$  is called the **dual puzzle**.

*Determination.* The number of periodic points of some QFT puzzles as a function of the period can be quite wild (see the examples in section 2.4). Hence, the analysis of periodic points requires a further assumption. We state it in terms of the projections, for  $N = 1, 2, \dots$ ,

$$i_N : V \rightarrow \bigcup_{k \leq N} V_k, \quad v \mapsto i^{(|v|-N)^+}(v).$$

$i_N$  extends to a map  $i_N : X_V \rightarrow \left(\bigcup_{k \leq N} V_k\right)^{\mathbb{N}}$  in a natural way.

**Definition 1.8.** A puzzle  $V$  is **determined** if for all  $w \in V$ , and  $v \in \mathcal{T}_i(w)$ ,  $i_1$  restricted to  $\{u \in V : u \succeq_f^1 v\}$  is one-to-one.

*Remarks.*

(1) Many puzzles are determined, for example, those defined as in Section 2.2 under the extra assumptions that: (i)  $T$  is one-to-one on the closure of each element of  $\mathcal{P}$ ; (ii) for each  $x \in M'$ ,  $\lim_n \text{diam}(\mathcal{P}^n(x)) = 0$  —  $\mathcal{P}^n(x)$  is the unique element (if it exists) of  $\mathcal{P}^n$  that contains  $x$ .

(2) There exist determined puzzles whose duals are not determined.

**1.2. Structure Theorem.** Let us first recall the notion of entropy-conjugacy from [3].

Let  $T : X \rightarrow X$  be a Borel map. Let  $h(T)$  be the supremum of the entropy of all  $T$ -invariant probability measures. Recall that if  $X$  is compact and  $T$  continuous then  $h(T)$  is just the topological entropy by the variational principle [34]. A subset  $X_0 \subset X$  is *entropy-negligible* if it is Borel and satisfies:

$$\tilde{h}(T, X_0) := \sup\{h(T, \mu) : \mu \text{ ergodic with } \mu(X_0) > 0\} < h(T),$$

that is,  $X_0$  is negligible in the usual sense for all large entropy measures, i.e., invariant and ergodic probability measures with entropy close to  $h(T)$ .

Two Borel maps  $T : X \rightarrow X$  and  $S : Y \rightarrow Y$  are **entropy-conjugate** if there exist entropy-negligible subsets  $X_0 \subset X$  and  $Y_0 \subset Y$  and a Borel isomorphism  $\Psi : X \setminus X_0 \rightarrow Y \setminus Y_0$  with  $\Psi \circ T = S \circ \Psi$ . The *constant* of this isomorphism is  $\max(\tilde{h}(T, X_0), \tilde{h}(S, Y_0))$ .

Recall also that a **Markov shift** (see [14] and also [10, 21, 23, 30, 31, 32], for background) is the set  $\Sigma(G)$  of all bi-infinite paths on a countable or finite directed graph  $G$  together with the left-shift  $\sigma$ :

$$\Sigma(G) = \{x \in G^{\mathbb{Z}} : \forall n \in \mathbb{Z} \ x_n \rightarrow x_{n+1} \text{ on } G\} \text{ and } \sigma((x_n)_{n \in \mathbb{Z}}) = (x_{n+1})_{n \in \mathbb{Z}}.$$

The Markov shifts defined by finite graphs are exactly the very much studied subshifts of finite type (of order 1) —see [22] for an introduction to this rich classical theory.

$X$  is *irreducible* if it contains a dense orbit (equivalently its graph is strongly connected). Any Markov shift has a *spectral decomposition* as a union of countably many irreducible ones (up to wandering orbits). The period of a subset  $U$  of  $X$  is

the greatest common divisor of all  $n \geq 1$  such that  $\sigma^k U \cap U \neq \emptyset$ . The *period* of  $X$  is the largest period of all non-empty open subsets of  $X$ .

A Markov shift is not compact unless it is a subshift of finite type. Its topological entropy is therefore defined as explained above for a general Borel system. Gurevič [12] proved that in the irreducible case this entropy is just, for any  $(a, b) \in G^2$ :

$$h(G) := h(\Sigma(G)) = \limsup_{n \rightarrow \infty} \frac{1}{n} \log \#\{v \in G^n : v_1 = a, v_1 \rightarrow v_2 \rightarrow \dots v_n = b\}$$

An irreducible Markov shift is said to be **SPR** (for *strongly positively recurrent*) [14]) if it admits an entropy-maximizing probability measure  $\mu$  which is exponentially filling, i.e., for any non-empty open subset  $U$  of  $X$ ,

$$\lim_{n \rightarrow \infty} \frac{1}{n} \log \mu \left( X \setminus \bigcup_{k=0}^n \sigma^{-k} U \right) < 0$$

Such Markov shifts are closest to being of finite type by a number of results (see, e.g., Gurevič [13], Sarig [31], Savchenko [14] among others).

Finally recall that the *natural extension* of a map  $T : X \rightarrow X$  is the “smallest” extension that is invertible, i.e., it is  $\tilde{T} : \tilde{X} \rightarrow \tilde{X}$  with  $\tilde{X} := \{x \in X^{\mathbb{Z}} : \forall n \in \mathbb{Z} T(x_n) = x_{n+1}\}$  and  $\tilde{T}((x_n)_{n \in \mathbb{Z}}) = (Tx_n)_{n \in \mathbb{Z}}$ .

We may now state our main result:

**Theorem 1** (Main Result). *Let  $V$  be a puzzle.*

(1) *If  $V$  (or its dual puzzle) is a  $*$ -QFT puzzle, the natural extension of the dynamics of  $V$  is entropy-conjugate with constant at most  $h_C(V)$  to a Markov shift  $\Sigma(G)$ .*

(2) *If  $V$  (or its dual puzzle) is QFT, then, for every  $H > h_C(V)$ , the spectral decomposition of  $\Sigma(G)$  contains only finitely many irreducible Markov shift with entropy  $\geq H$ . Moreover these Markov shifts are SPR. More precisely their entropies at infinity (see Definition 1.9 below) are at most  $h_C(V) + h_{\text{wloc}}(V)$ .*

(3) *If  $V$  is both QFT and determined then, for each number  $\epsilon > 0$ , integer  $N_0$  and finite part  $\mathcal{D}_0$  of  $\mathcal{D}$ , there exists an integer  $N \geq N_0$  and a large finite part  $\mathcal{D}_N \supset \mathcal{D}_0$  of  $\mathcal{D}$  with the following property. There is a period-preserving bijection between the periodic loops on  $\mathcal{D}$  that meet  $\mathcal{D}_N$  and the periodic orbits of  $i_N(X_V)$  after discarding a number  $p_n^0$  of the  $n$ -periodic orbits of  $i_N(X_V)$  satisfying:*

$$\limsup_{n \rightarrow \infty} \frac{1}{n} \log p_n^0 \leq h_C(V) + h_{\text{wloc}}(V) + \epsilon.$$

The proof of this theorem, presented in Sections 4 and 5, relies on the adaptation to puzzles of the “complete” Hofbauer diagram developed in [3] for subshifts.<sup>1</sup>

### 1.3. Dynamical consequences.

<sup>1</sup>This “complete” variant essentially removes “accidental” identifications, i.e., of the type  $T(A) = T(B)$  where  $A$  and  $B$  are distinct elements of the partition whereas  $T(A) = T(B)$  does not belong to that partition. This variant is necessary for the precise counting of periodic orbits as we explained in [8] (it also simplifies the proof of the partial isomorphism, see Section 4).



1.3.1. *Maximum measures.* The Structure Theorem gives the following, using Gurevič's result on maximum measures for Markov shifts.

**Theorem 2** (Maximum Measures). *A QFT puzzle has at least one and at most finitely many maximum measures and those are in bijection with the SPR Markov subshifts with maximum entropy. The natural extensions of these measures are the products of a Bernoulli scheme by a cyclic permutation. Moreover, the periods of the (permutations of the) measures and those of the irreducible subshifts coincide.*

This follows immediately from the Structure Theorem and Gurevič results for Markov shifts, as explained in Section 7.1.

*Remark.* The proof that the QFT condition implies the existence of a maximum measure is closely related to a joint work [9] with S. Ruette.

1.3.2. *Zeta functions.* We turn to the numbers of periodic points.

**Theorem 3** (Zeta Functions). *Assume that  $V$  is a QFT puzzle which is also determined. Fix a large integer  $N$  and consider the reduced zeta function:*

$$\zeta_N(z) := \exp \sum_{n \geq 1} \frac{z^n}{n} \#\{x \in i_N(X_V) : \sigma^n(x) = x\}.$$

$\zeta_N$  is holomorphic on  $|z| < e^{-h_{\text{top}}(V)}$  and has a meromorphic extension to  $|z| < e^{-h_c(V) - h_{\text{wloc}}(V)}$ . Its singularities near the circle  $|z| = e^{-h_{\text{top}}(V)}$  are exactly poles at

$$e^{2i\pi k/p_i} e^{-h_{\text{top}}(V)} \quad i = 1, \dots, r \quad k = 0, \dots, p_i - 1$$

(with multiplicities equal to repetitions in this list) where  $p_1, \dots, p_r$  are the periods of the distinct maximum measures  $\mu_1, \dots, \mu_r$ .

Moreover, for each  $\epsilon > 0$ , the poles of  $\zeta_N(z)$  in  $|z| < e^{-h_c(V) - h_{\text{wloc}}(V) - \epsilon}$  are independent of  $N$ : for  $N', N > N(V, \epsilon)$ ,  $\zeta_{N'}(z)/\zeta_N(z)$  extends to a holomorphic function on this disk.

This is, technically, the most delicate result as we have to go from entropy estimates (which confuses very close points) to counting (this is of course why the determinacy assumption is required) —see Section 7.2.

*Remark.*

1. Even in the special case of *subshifts* of quasi-finite type, this strengthens [8]. An interesting example of such subshifts is obtained by taking the symbolic dynamics of any piecewise monotonic map with non-zero entropy (see [8]). The constraint entropy is zero in these cases. Hence the above says that its zeta function has a meromorphic extension to  $|z| < 1$ . For the symbolic dynamics of piecewise monotonic maps (which are subshifts of quasi-finite type), this had been shown by Milnor and Thurston [26].

2. Counting the *projections* at level  $N$  of periodic points instead of the periodic points themselves is necessary as it not even true that  $\#\{x \in X_V : \sigma^n(x) = x\} < \infty$  for an arbitrary QFT puzzles.

1.3.3. *Semi-local zeta functions for SPR Markov shifts.* The proof of this result relies on a similar (and new) result for SPR Markov shifts. First, define the "entropy at infinity":

**Definition 1.9.** *Let  $G$  be a countable, oriented, irreducible graph. The **entropy at infinity** of  $G$  is:*

$$(1) \quad h_\infty(G) = \inf_{F \subset \subset G} \inf_{\mu_0 > 0} \sup \{h(\sigma, \mu) : \mu([F]) < \mu_0\}.$$

where  $F$  ranges over the finite subgraphs of  $G$  and  $[F] := \{x \in \Sigma(G) : x_0 \in F\}$ .

*Remarks.* (1)  $h_\infty(G) = -\infty$  if  $G$  is finite.

(2)  $H \subset G$  implies that  $h_\infty(H) \leq h_\infty(G)$  as both are infimum over  $\mu_0 > 0$  and  $F \subset \subset G$  of  $\sup\{h(\sigma, \mu) : \mu([F]) < \mu_0\}$  and  $\sup\{h(\sigma, \mu) : \mu([F]) < \mu_0$  and  $\mu([G \setminus H]) = 0\}$ , respectively.

(3) This definition was motivated by the observation of Ruelle [30] that it is related the combinatorial quantities considered by Gurevič and Zargaryan [15] (see Proposition 6.1). In particular,  $h_\infty(G) < h(G)$  iff  $G$  is SPR.

**Theorem 4.** *Let  $\Sigma(G)$  be an irreducible Markov shift with finite Gurevic entropy  $h(G)$ . For any finite subset  $F \subset \subset G$ , the **semi-local zeta function** of  $G$  at  $F$ :*

$$\zeta_F^G(z) := \exp \sum_{n \geq 1} \frac{z^n}{n} \#\{x \in \Sigma(G) : \sigma^n(x) = x \text{ and } \{x_0, \dots, x_{n-1}\} \cap F \neq \emptyset\}$$

is holomorphic on  $|z| < e^{-h(G)}$  and has a meromorphic extension to  $|z| < e^{-h_\infty(G)}$ .

Moreover, for every  $\epsilon > 0$ , there exists  $F_0 \subset \subset G$  such that, if  $F, F'$  are two finite subsets with  $F_0 \subset F, F' \subset \subset G$ , then

$$\frac{\zeta_{F'}^G(z)}{\zeta_F^G(z)} \text{ is holomorphic and non-zero on } |z| < e^{-h_\infty(G) - \epsilon}.$$

*Remarks.*

(1) This is new. In fact, even the case of the usual *local zeta function*, i.e., with  $F$  reduced to a single vertex had not been observed to our knowledge. Notice that, even in this case, the above definition differs from that of [32] (which has usually a non-polar singularity at  $z = e^{-h(G)}$  so has no meromorphic extension) but is the same as [14].

(2) The theorem is trivial if  $h_\infty(G) = h(G)$ , that is, if  $G$  is not SPR (see Proposition 6.1). In the opposite extreme, for subshifts of finite type, i.e.,  $G$  finite, this asserts that  $\zeta_H^G$  extends to a meromorphic extension over  $\mathbb{C}$ . Of course, in this case  $\zeta_H^G = \zeta^G / \zeta^{G \setminus H}$  in terms of the classical Artin-Mazur zeta functions so the semi-local zeta function extends in fact meromorphically over the Riemann sphere, i.e., is a rational function.

(3) The conclusion of Theorem 4 is false for the *full zeta function* (i.e.,  $\zeta^G$ ).  $\zeta^G$  is not always defined as a formal series and, even if it is, can have zero radius of convergence or it can have various types of singularities (see [14, Example 9.7]).

(4)  $\zeta_F^G(z) / \zeta_H^G(z)$  is meromorphic over  $|z| < \exp -h_\infty(G)$  but it is not necessarily holomorphic and non-zero. If  $G_n$  is the complete oriented graph on  $\{1, 2, \dots, n\}$ , we have  $h(G) = \log 3$ ,  $h_\infty(G_3) = -\infty$ ,  $\zeta^{G_3}(z) = \zeta_{G_3}^{G_3}(z) = 1/(1 - 3z)$  and  $\zeta_{\{0\}}^{G_3}(z) = \zeta^{G_3}(z) / \zeta^{G_2}(z) = (1 - 2z)/(1 - 3z)$ .

(5) The maximum radius of a meromorphic extension<sup>2</sup> of the semi-local zeta functions may be strictly larger than  $\exp -h_\infty(G)$ . There are even Markov shifts for which the radius of meromorphy of the local zeta functions varies (see the appendix for an example where some local zeta functions are rational and other have a finite radius of meromorphy). One can wonder if these values and for instance their supremum has a dynamical significance besides the obvious fact that if  $g \in G$  and  $g' \in G'$  define the same local zeta functions, the corresponding shifts are almost isomorphic in the sense of [2]. One would like to "patch together" all the partial informations provided by all the (semi) local zeta functions.

The proof of Theorem 4 relies on the generalization of an algebraic formula decomposing the determinant of finite matrices –see section 6. In the special case of a *loop graph*, i.e., the disjoint union of  $f_n$  loops for each length  $n \geq 1$  based at a single vertex  $a$  (see the Appendix), with  $F$  reduced to  $\{a\}$ ,  $h_\infty(G) = \limsup_{n \geq \infty} (1/n) \log f_n$  and the determinantal formula coincides with the well-known identity  $\zeta_a(f) = (1 - f_a(z))^{-1}$ , where  $f_a(z) := \sum_{n \geq 1} f_n z^n$ , so the above reduces exactly to the proof of [14, Prop. 9.2].

1.3.4. *Equidistribution of the periodic points.* The periodic points are equidistributed w.r.t. a suitable measure of maximum entropy:

**Theorem 5** (Equidistribution of periodic points). *Assume that  $V$  is a QFT puzzle which is determined. Let  $\mu_1, \dots, \mu_r$  be the distinct maximum measures and  $p_1, \dots, p_r$  their periods,  $p = \text{ppcm}(p_1, \dots, p_r)$ .*

*Fix a sufficiently large integer  $N$  and consider, for  $n \in p\mathbb{Z}$ , the measures:*

$$\mu_n^N := \sum_{x \in i_N(X_V) | \sigma^n(x) = x} \delta_x$$

*Then, in the weak star topology,*

$$\lim_{n \rightarrow \infty, n \in p\mathbb{Z}} \frac{1}{\mu_n^N(X_V)} \mu_n^N = \frac{1}{\sum_i p_i} \sum_{i=1}^r p_i \mu_i.$$

This is also deduced of a result of Gurevič and Savchenko [14] for SPR Markov shifts.

1.4. **Classification of QFT puzzles.** In the same way as QFT subshifts [8], QFT puzzles can be classified up to entropy-conjugacy by their entropy and periods. Using the classification result [2] obtained with Boyle and Gomez for SPR Markov shifts, the above structure theorem implies:

**Theorem 6** (Classification). *The natural extension of QFT puzzles are completely classified up to entropy-conjugacy by the following data: the topological entropy and the list, with multiplicities, of the periods of the finitely many maximum measures.*

This gives a very precise meaning to our assertion that complexity assumptions (defining QFT puzzles) in fact characterize them from the point of view of complexity.

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<sup>2</sup>See the Appendix for formal definitions.

**1.5. Smooth maps defining QFT puzzles.** We describe the class of smooth maps whose symbolic dynamics are QFT puzzles which will both provide interesting examples of such puzzles and yield a new proof of variants of previous results [6] about the dynamics of such maps.

Let  $F : M \rightarrow M$  be a  $C^\infty$  smooth map of a  $d$ -dimensional compact manifold. The main assumption is that  $F$  is **entropy-expanding**, which is defined as follows.

The *codimension one entropy* [6] is

$$h^{d-1}(F) = \sup\{h_{\text{top}}(F, \sigma) : \sigma \subset\subset N^{d-1}\}.$$

Here  $\sigma \subset\subset N^{d-1}$  means that  $\sigma$  ranges over the compact subsets of arbitrary  $C^\infty$   $d-1$ -dimensional submanifolds. Recall that  $h_{\text{top}}(F, \sigma)$  counts the number of orbits starting from the non necessarily invariant set  $\sigma$  — see [34]:

$$h_{\text{top}}(F, \sigma) = \lim_{\epsilon \rightarrow 0} \limsup_{n \rightarrow \infty} r(\epsilon, n, \sigma).$$

The *entropy-expanding condition* [6] is:

$$h^{d-1}(F) < h_{\text{top}}(F) := h_{\text{top}}(F, M).$$

It is an open condition in the  $C^\infty$  topology [6]. Entropy-expanding maps form a natural class of multi-dimensional non-uniformly expanding maps. It includes small couplings of interval maps [4], e.g.,

$$(x, y) \mapsto (1.5 - x^2 + \epsilon y, 1.8 - y^2 + \epsilon x)$$

for small enough  $\epsilon$ . Such coupled interval maps are natural examples of multi-dimensional non-uniformly expanding maps with critical points but their ergodic theory has resisted all other approaches up to now, despite all the results following [33] in the case where one of the two factor is assumed to be uniformly expanding.

We shall additionally assume that there exists a *good partition*  $\mathcal{P}$  for  $F$ , i.e., with the following properties:

- $\mathcal{P}$  is finite;
- each element of  $\mathcal{P}$  is the closure of its interior;
- the boundary of each element of  $\mathcal{P}$  is the image of a compact subset of  $\mathbb{R}^{d-1}$  by a  $C^\infty$  smooth map;
- the restriction of  $f$  to the closure of any element  $A$  of  $\mathcal{P}$ ,  $f|_{\bar{A}}$ , is one-to-one.
- for each  $n \geq 1$ , each  $\mathcal{P}$ ,  $n$ -cylinder:

$$A_0 \cap F^{-1}A_1 \cap \dots \cap F^{-n+1}A_{n-1} \quad A_i \in \mathcal{P}$$

has only finitely many *almost connected components*: maximum subsets which cannot be split into two subsets at a positive distance;

- we have a uniform bound

$$\sup_x \#\{k \in \mathbb{N} : F^k(x) \in \partial\mathcal{P}\} < \infty.$$

*Remark.* Of course not all  $C^\infty$  maps of compact manifolds have such partitions (for instance, there are infinitely-to-one smooth maps, even in the entropy-expanding category). But we believe that generic  $C^\infty$  maps have good partitions.

Given  $F$  and a good partition  $\mathcal{P}$  as above, we define the *associated puzzle* to be  $(V, i, f)$  with  $V = \sqcup_{n \geq 0} V_n$  where:

- $V_n$  is the collection of almost connected components of  $\mathcal{P}$ ,  $n$ -cylinders;

- $i, f : V_{n+1} \rightarrow V_n$  are the maps defined by  $i(u) = v$  and  $f(u) = w$  if  $v \supset u$  and  $w \supset F(u)$ .

We shall see the:

**Theorem 7** (Puzzles of entropy-expanding maps). *Let  $T : M \rightarrow M$  be a  $C^\infty$  smooth map of a  $d$ -dimensional map. Assume that  $T$  is entropy-expanding and admits a good partition  $\mathcal{P}$ . Then the puzzle associated to  $(T, \mathcal{P})$  is QFT and determined. More precisely,  $h_{\text{wloc}}(V) = 0$  and  $h_{\mathcal{C}}(V) \leq h^{d-1}(T)$ .*

*In particular, such maps have finitely many maximum measures and, up to the identifications given by some partition, their periodic points define zeta functions with meromorphic extensions to  $|z| < \exp -h^{d-1}(T)$ .*

These results are stated more precisely as Theorem 8 and its Corollaries 8.2-8.3.

*Remark.* One could relax the assumption of smoothness to  $C^r$  smoothness with  $r \geq 1$  provided one strengthens the entropy-expansion condition in the following way:

$$h^{d-1}(f) + \frac{d-1}{r} \log^+ \text{Lip}(f) < h_{\text{top}}(f)$$

(in fact our proofs needs only  $H^{d-1}(f) < h_{\text{top}}(f)$  where  $H^{d-1}(f)$  is the uniform codimension 1 entropy defined in [3]). We obtain then a new existence result, but the assumption of a good partition avoids the most interesting difficulties.

**Numbering.** All items are numbered consecutively within each section, except for the theorems.

**Acknowledgments.** J.-C. Yoccoz asked me about the relationship between Hofbauer's towers and the puzzles of complex dynamics a long time ago. M. Boyle was always encouraging at all the stages this work went through. S. Ruelle pointed out to me Proposition 6.1 and the link with  $h_\infty(G)$ . Last but not least, I am indebted to O. Sarig, especially with regard to my results about zeta functions for Markov shifts. His insights led me to the example given in the Appendix.

## 2. EXAMPLES OF PUZZLES

For  $v \in V$ , we denote by  $|v|$  the unique integer  $n$  such that  $v \in V_n$ . It is the order of  $v$ .

**2.1. Simplest example.** Let  $\sigma : \Sigma_+ \rightarrow \Sigma_+$  be an arbitrary one-sided subshift (i.e., a closed shift-invariant subset of  $\mathcal{A}^{\mathbb{N}}$  for some finite set  $\mathcal{A}$ , the shift being  $\sigma : (A_n)_{n \geq 0} \mapsto (A_{n+1})_{n \geq 0}$ ). We are going to define a puzzle  $V$  such that the corresponding dynamics  $X_V$  is topologically conjugate to this subshift  $\Sigma_+$ .

For each  $n \geq 0$ , let  $V_n$  be the set of words of length  $n$  that appear in  $\Sigma_+$ , i.e., sequences  $x_0 \dots x_{n-1}$  such that  $y_{i+k} = x_i$  for  $i = 0, \dots, n-1$  for some  $y \in X$  (by convention,  $V_0 = \{\emptyset\}$  where  $\emptyset$  is the null word). Define the two maps  $i$  and  $f$  by:

$$\begin{aligned} i(A_1 \dots A_n) &= A_1 \dots A_{n-1} && \text{rightmost delete} \\ f(A_1 \dots A_n) &= A_2 \dots A_n && \text{leftmost delete} \end{aligned}$$

The conjugacy  $h : X_V \rightarrow \Sigma_+$  is given by  $h((A_1 \dots A_n)_{n \geq 0}) = (A_{n+1})_{n \geq 0}$ .

**2.2. From dynamics to puzzles.** Let  $T : M \rightarrow M$  be a self-map. Let  $\mathcal{P}_0 = \{M\}, \mathcal{P}_1, \mathcal{P}_2 \dots$  be a sequence of finite partitions satisfying

$$\mathcal{P}_n \preceq \mathcal{P}_{n+1} \text{ and } T^{-1}\mathcal{P}_n \preceq \mathcal{P}_{n+1}$$

(where  $\mathcal{P} \preceq \mathcal{Q}$  means that  $\mathcal{P}$  is less fine than  $\mathcal{Q}$ : each element of  $\mathcal{P}$  is a union of elements of  $\mathcal{Q}$ ).

This data defines a puzzle as follows. Let  $V$  be the disjoint union of  $V_n = \mathcal{P}_n$ ,  $n \geq 0$ . Let  $i(v) = w$  if  $w$  is the element of  $\mathcal{P}_n$  containing  $v \in \mathcal{P}_{n+1}$ . Let  $f(v) = w$  if  $w$  is the element of  $\mathcal{P}_n$  containing  $T(v)$  for  $v \in \mathcal{P}_{n+1}$ . The above assumptions ensure that this is a well-defined puzzle.

Let us give several applications of this construction.

- Let  $\mathcal{P}$  be some finite partition and let  $\mathcal{P}_n = \mathcal{P} \vee T^{-1}\mathcal{P} \vee \dots \vee T^{-n+1}\mathcal{P}$ . The corresponding puzzle is topologically conjugate to the usual symbolic dynamics, i.e., the left shift,  $\sigma : (A_n)_{n \geq 0} \mapsto (A_{n+1})_{n \geq 0}$  acting on:

$$(2) \quad \overline{\{A \in \mathcal{P}^{\mathbb{N}} : \exists x \in M \forall n \geq 0 T^n x \in A_n\}} \subset \mathcal{P}^{\mathbb{N}}.$$

Observe the following

**Fact 2.1.** *Any continuous map  $T$  on a Cantor set  $K$  can be realized, up to topological conjugacy, as a puzzle.*

PROOF: Let  $\mathcal{Q}_n$ ,  $n \geq 1$ , be a sequence of partitions of  $K$  into closed-open sets with diameters going to zero. Let  $\mathcal{P}_{n+1} = \mathcal{Q}_{n+1} \vee \mathcal{P}_n \vee T^{-1}\mathcal{P}_n$ . It is then easy to see that the dynamics of the puzzle thus defined is conjugate to that of  $T$ .  $\square$

We see that the dynamics of puzzles are even more diverse (and possibly wild) than that of subshifts. For instance, they can have infinite entropy or be without measures of maximum entropy.

- Let  $\mathcal{P}$  be some finite partition and let  $\mathcal{P}_n$  be the set of connected components of the elements of  $\mathcal{P} \vee T^{-1}\mathcal{P} \vee \dots \vee T^{-n+1}\mathcal{P}$ . This is the form used in complex dynamics [24].

**2.3. Puzzles with finitely many irreducible vertices.** We prove Lemma 1.4, i.e., that the dynamics of a puzzle with finitely many irreducible vertices is (topologically conjugate to) a subshift of finite type.

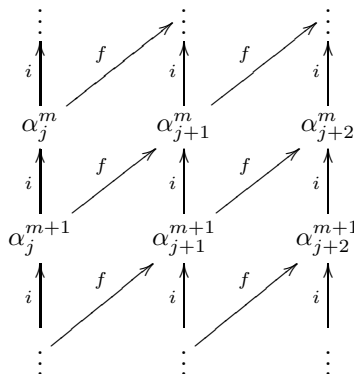
Let  $n_0$  be the largest integer such that  $V_{n_0}$  contains a minimal left constraint. Let  $n$  be an arbitrary integer larger than  $n_0$ . Recall the map  $i_n : X_V \rightarrow V_n^{\mathbb{N}}$ . To prove the lemma, it is enough to see that  $i_n(X_V)$  is a subshift of finite type (easy since  $v$  reducible implies  $F_V([v]_V) = [f(v)]_V = \bigcup_{w \in i^{-1}(v)} [w]_V$ ) and that all the subshifts obtained for large  $n$  are topologically conjugate.

Let  $n > n_0$ . Consider the finite graph  $\Gamma_n$  whose vertices are the elements of  $V_n$  and whose arrows are defined by:

$$u \rightarrow_{\Gamma_n} v \iff \exists w \in V_{n+1} i(x) = u \text{ and } f(x) = v.$$

Observe for future reference that, because of the definition of a reducible vertex,  $w$  above is uniquely determined by  $u$  and  $v$ .

Let  $\Sigma_n \subset V_n^{\mathbb{N}}$  be the subshift of finite type defined by  $\Gamma_n$ . We claim that  $i_n(X_V) = \Sigma_n$ .

FIGURE 1. Construction of  $\alpha^{m+1}$ .

Observe first that  $i_n(X_V) \subset \Sigma_n$ . Indeed, for  $x \in X_V$ ,  $(F_V^{k+1}x)_n = f((F_V^k x)_{n+1})$  by definition of  $F_V$  and  $i(F_V^k x)_{n+1} = (F_V^k x)_n$  by definition of  $X_V$  so that  $(F_V^k x)_n \rightarrow_{\Gamma_n} (F_V^{k+1}x)_n$ , therefore  $i_n(x) \in \Sigma_n$ .

We turn to the converse inclusion. Let  $\alpha^0 \in \Sigma_n$  for some  $n > n_0$ . We are going to define inductively  $\alpha^m \in V_{n+m}^{\mathbb{N}}$ ,  $m \geq 1$ , such that, for all  $m \geq 0$ ,  $j \in \mathbb{N}$  and  $0 \leq k \leq m$ ,

$$(3) \quad (i) \ i^k(\alpha_j^m) = \alpha_j^{m-k}, \quad (ii) \ \alpha_j^m \succeq_f^k \alpha_{j+k}^{m-k}, \quad (iii) \ \alpha_{j+1}^m \in f(i^{-1}(\alpha_j^m)).$$

Indeed, setting  $x_k = i^{n-k}(\alpha_0^0)$  for  $k \leq n$  and  $x_k = \alpha_0^{k-n}$  for  $k \geq n$ , we get  $x \in X_V$  by (i) such that  $\alpha^0 = i_n(x)$ , as  $f^k(\alpha_0^0) = \alpha_k^0$  by (ii).

Observe that (3) holds for  $m = 0$  because of the definition of  $\Gamma_n$ . Let us assume that  $\alpha_j^p$  has been defined for  $p \leq m$  and all  $j \in \mathbb{N}$  so that eq. (3) is satisfied. For  $j \in \mathbb{N}$ , let us build  $\alpha_j^{m+1}$  satisfying (3).

Let  $\alpha_j^{m+1} \in f^{-1}(\alpha_{j+1}^m) \cap i^{-1}(\alpha_j^m)$  (this intersection is not empty by (iii), eq. (3) and it is unique because  $\alpha_j^{m+1}$  is  $f$ -reducible). Let us check eq. (3) for  $m+1, j$ .  $i^{k+1}(\alpha_j^{m+1}) = i^k(\alpha_j^m)$  hence (i) is satisfied.  $f(\alpha_j^{m+1}) = \alpha_{j+1}^m$  and  $\alpha_j^{m+1}$  is  $f$ -reducible by the main assumption. Thus  $\alpha_j^{m+1} \succeq_f^k \alpha_{j+k}^{m+1-k}$  for  $k = 1$  and for  $1 < k \leq m$  by the induction hypothesis. This is (ii). As  $\alpha_j^{m+1} \succeq_f^1 \alpha_j^m$ , the  $i$ -tree below  $\alpha_j^{m+1}$  is mapped onto the  $i$ -tree below  $\alpha_j^m$ . This gives (iii), completing the induction.

Finally, one observes that  $\alpha^{p+1} = i_{p+1}(\underline{x})$  is uniquely defined by  $\alpha^p = i_p(\underline{x})$  so that the natural projection  $i_{p+1}(X_V) \rightarrow i_p(X_V)$  is in fact a homeomorphism. This finishes the proof of Lemma 1.4.

**2.4. \*-QFT puzzles with nasty dynamics.** We give examples of \*-QFT puzzles with infinitely or no maximum measures.

Let  $\Sigma_0 = \{0^\infty\}, \Sigma_1, \Sigma_2, \dots$  be a sequence of subshifts of finite type over disjoint alphabets. Assume that the Markov order of  $\Sigma_n$  is at most  $n$  (i.e.,  $A \in \Sigma_n$  iff  $A_k \dots A_{k+n-1}$  is a word in  $\Sigma_n$  for all  $k \geq 0$ ) and that  $h_{\text{top}}(\Sigma_n) > 0$  for all  $n \geq 1$ . We are going to build a puzzle which is conjugate to  $\bigcup_{n \geq 0} \Sigma_n$ . Taking  $h_{\text{top}}(\Sigma_n) = \log 2$  for all  $n \geq 1$ , or  $h_{\text{top}}(\Sigma_n) \nearrow \log 2$  as  $n \rightarrow \infty$ , shall yield the required examples.

Let  $L_n(\Sigma_k)$  be the set of words of length  $n$  appearing in  $\Sigma_k$ . The puzzle will be  $(V, i, f)$  defined as follows:

Let  $V_0 = \{\emptyset\}$  (the empty word) and  $V_n = \sqcup_{0 \leq k \leq n} L_n(\Sigma_k)$ .

Let  $w := A_1 \dots A_n \in V_n$ . If  $w \in L_n(\Sigma_n)$ , then  $f(w) = i(w) = 0^{n-1}$ . Otherwise, let  $f(A_1 \dots A_n) = A_2 \dots A_n$  and  $i(A_1 \dots A_n) = A_1 \dots A_{n-1}$ .

The irreducible vertices of  $V_n$  are then the elements  $w$  of  $L_n(\Sigma_n)$  which are mapped by  $f$  to  $0^{n-1}$  as the tree  $\mathcal{T}_i(0^{n-1})$  is not isomorphic to  $\mathcal{T}_i(w)$  (which is essentially the puzzle for  $\Sigma_n$ ). For  $n > N$ , all these constraints are confused with  $0^n$  by  $i_N$ . Thus at a given level  $N$ , the number of distinguishable irreducible vertices in  $V_n$  is bounded independently of  $n$  so that  $h_C(V) = 0$ . Thus  $V$  is indeed a \*-QFT puzzle.

**2.5. QFT puzzles with bad zeta functions.** Let us describe a QFT puzzle with infinitely many periodic orbit of any given length so that the zeta function defined from the periodic points (and not their projections) is not even well-defined as a formal series.

Pick a sequence of positive integers  $p_1, p_2, \dots$  such that  $\#p^{-1}(k) = \infty$  for all  $k \geq 1$ . Modify the previous construction to make  $\Sigma_n$  a periodic orbit of length  $p_n$ , except for  $\Sigma_1$  which can be any subshift of finite type with nonzero entropy. Then  $h_C(V) = h_{\text{wloc}}(V) = 0$  so  $V$  is indeed a QFT puzzle.

*Remark.* Obvious adaptations of this construction yield examples with arbitrary growth rates of the number of periodic orbits.

### 3. BASIC PROPERTIES

#### 3.1. Some properties of $f$ -reducibility.

**Lemma 3.1.** *If  $i(u) = i(u')$ ,  $f^k(u) = f^k(u')$  and  $u \succeq_f^k v$  and  $f : \mathcal{T}_i(f^{l-1}(u')) \rightarrow \mathcal{T}_i(f^l(u'))$ ,  $l = 1, \dots, k$  are graph isomorphisms then  $u = u'$ . In particular,*

$$(4) \quad i(u) = i(u') \text{ and } u \succeq_f^k w \text{ and } u' \succeq_f^l w \implies k = l \text{ and } u = u'.$$

PROOF: (4) clearly follows from the first claim. For  $k = 0, 1$ , this claim follows from the definition of  $\succeq_f^k$ . Assume the claim for some  $k - 1 \geq 0$ . Now,  $i(f^{k-1}(u)) = f^{k-1}(i(u)) = f^{k-1}(i(u')) = i(f^{k-1}(u'))$  and both  $f^{k-1}(u) \succeq_f^1 v$  and  $f : \mathcal{T}_i(f^{k-1}(u')) \rightarrow \mathcal{T}_i(v)$  is an isomorphism. This implies that  $f^{k-1}(u) = f^{k-1}(u') =: w$  by the definition of  $\succeq_f^1$ . Now  $i(u) = i(u')$  and  $u \succeq_f^{k-1} w$  and  $f : \mathcal{T}_i(f^{l-1}(u')) \rightarrow \mathcal{T}_i(f^l(u'))$ ,  $l = 1, \dots, k - 1$ , so the induction hypothesis implies  $u = u'$ .  $\square$

**Lemma 3.2.** *If  $i(u) \succeq_f^k i(v)$  and  $f^k(u) = v$  with  $|u|, |v| \geq 1$  and  $k \geq 0$ , then  $u \succeq_f^k v$ . In particular, if  $u$  with  $|u| > 1$  is  $f$ -irreducible, then so is  $i(u)$ .*

PROOF:  $i(u) \succeq_f^k i(v)$  implies that the  $i$ -trees below  $i(u)$  and  $i(v)$  are isomorphic through  $f^k$ . As  $i \circ f = f \circ i$ , this implies the same for the sub- $i$ -trees below  $u$  and  $v$ . Assuming by contradiction that  $u \not\succeq_f^k v$  we obtain that there exists  $w \in i^{-1}(i(u))$ ,  $w \neq u$  with  $f^k(w) = f^k(u)$ , but this would contradict that  $f^k|_{\mathcal{T}_i(i(u))}$  is one-to-one.  $\square$



**3.2. Natural extension and duality.** Except in trivial cases, the dynamics  $F_V : X_V \rightarrow X_V$  is non-invertible. To obtain an invertible dynamical system, one goes to the *natural extension*. It can be described as  $(\underline{X}_V, F_V)$  with:

$$\begin{aligned} \underline{X}_V &= \{(v_{n,p})_{n,p} : \forall (n,p) \in \mathbb{N} \times \mathbb{Z} \ i(v_{n+1,p}) = f(v_{n+1,p-1}) = v_{n,p} \in V_n\} \\ F_V &: (v_{n,p})_{n,p} \mapsto (f(v_{n+1,p-1}))_{n,p}. \end{aligned}$$

The distance on  $\underline{X}_V$  is defined as:  $d(x, y) = \sum_{n \geq 0} 2^{-n} d(x_{-n}, y_{-n})$ .

Remark that  $(\underline{X}_V, F_V)$  is homeomorphic to the usual realization of the natural extension:  $\{(\underline{v}_p)_{p \in \mathbb{Z}} \in X_V^{\mathbb{Z}} : \forall p \in \mathbb{Z} \ F_V(\underline{v}_{p-1}) = \underline{v}_p\}$  with  $(\underline{v}_p)_{p \in \mathbb{Z}} \mapsto (F_V(\underline{v}_p))_{p \in \mathbb{Z}}$ .

The symmetry of the roles of  $i$  and  $f$  gives rise to a **duality** between puzzles: just exchange the maps  $i$  and  $f$  associated to a puzzle  $(V, i, f)$ . We denote by  $(V^*, i^*, f^*)$  the resulting puzzle. The natural extension of their dynamics  $\overline{\sigma_V}$  and  $\overline{\sigma_{V^*}}$  are inverse of each other, as the description of the natural extensions given above makes it obvious.

*Remark.* As it was already the case for subshifts of quasi-finite type [8],  $h_C(V^*)$  may be different from  $h_C(V)$ . It may indeed occur that  $h_C(V) < h_{\text{top}}(V)$  and  $h_C(V^*) = h_{\text{top}}(V^*)$  (or the other way around). This implies trivially that  $h_{\text{wloc}}(V^*)$  might be different from  $h_{\text{wloc}}(V)$ . On the other hand, if  $\mu$  is an invariant probability measure of  $(X_V, F_V)$ ,  $\underline{\mu}$  the corresponding one for the natural extension and  $\mu^*$  the one for the dual puzzle dynamics,

$$h(F_{V^*}, \mu^*, 2\epsilon) \leq h(F_V, \underline{\mu}, 2\epsilon) \leq h(F_V, \mu, \epsilon) \leq h(F_V, \underline{\mu}, \epsilon) \leq h(F_{V^*}, \mu^*, \epsilon/2)$$

for all  $\epsilon > 0$ . To see, e.g., the second inequality above, observe that, letting  $n_0 := \log \epsilon^{-1} / \log 2$ :

$$[\forall 0 \leq k < n \ d(x_k, y_k) < \epsilon] \implies [\forall n_0 \leq k < n - n_0 \ d(F_V^k x, F_V^k y) < 2\epsilon].$$

#### 4. MEASURE-THEORETIC STRUCTURE

In this section we begin the proof of the structure theorem (Theorem 1). We first introduce the Markov shift which underlies our analysis and then we explain its consequences at the level of entropy-conjugacy. The proof then has three stages: (i) the Markov shift is shown to be measurably conjugate to a part of the natural extension of the puzzle dynamics; (ii) the entropy of the measures living on the excluded part are bounded, yielding claim (1) of the Theorem; (iii) the entropy “at infinity” in the Markov diagram is also controlled, yielding claim (2) of the Theorem. Claim (3), on the periodic points, is proved in the next section.

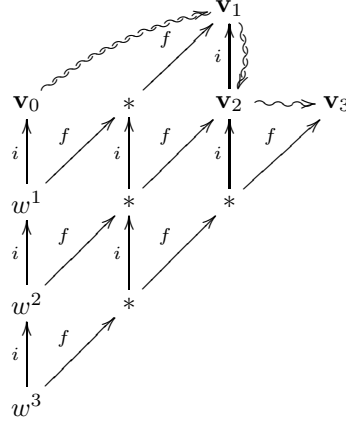
*Remark.* We assume in this proof that  $h_C(V)$  is the entropy of the sequence of  $f$ -irreducible vertices of  $V$ . We leave the entirely similar case when  $h_C(V)$  is given by the dual puzzle to the diligent reader.

**4.1. The complete Markov diagram.** The key object is the following countable oriented graph.

**Definition 4.1.** *The complete Markov diagram of a puzzle  $V$  is a countable, oriented graph  $\mathcal{D}$  defined as follows. Its vertices are the  $f$ -irreducible vertices of  $V$ . Its arrows are the following:*

$$(5) \quad v \rightsquigarrow w \iff \exists u \in V \ i(u) = v \text{ and } u \succeq_f w.$$

Notice that because of Lemma 3.1,  $u$  in eq. (5) is unique given  $v \rightsquigarrow w$ .

FIGURE 2. Construction of  $w^3$  from  $v_0 v_1 v_2 v_3$  as in Proposition 4.2.

*Remark.* If  $V$  is in fact a subshift over alphabet  $V_1$ , this complete Markov diagram reduces to the one introduced in [3]. Under the additional assumption that there are no "contingente" identifications, i.e.,  $F_V^{|v|}[v] = F_V^{|w|}[w]$  only if  $w = f^{|v|-|w|}(v)$  (assuming  $|v| \geq |w|$ ), this further reduces to the Hofbauer diagram [16].

Let  $\Sigma_+(\mathcal{D})$  be the associated one-sided subshift:

$$\Sigma_+(\mathcal{D}) = \{\underline{v} \in V^{\mathbb{N}} : v_0 \rightsquigarrow v_1 \rightsquigarrow v_2 \rightsquigarrow \dots\}.$$

We build a conjugacy from the Markov shift onto (a part of) the puzzle dynamics.

**Proposition 4.2.** *Let  $\underline{v} \in \Sigma_+(\mathcal{D})$  and  $n \geq 0$ . There exists a unique  $w^{(n)} \in V$  such that:*

- (i)  $i^n(w^{(n)}) = v_0$ ;
- (ii) for all  $k = 0, \dots, n$ :  $i^k w^{(n)} \succeq_f v_{n-k}$ .

Moreover, the following property holds:

- (iii)  $i(w^{(n+1)}) = w^{(n)}$ .

Figure 2 gives a typical example of the construction of  $w^n$ .

PROOF: We inductively define sequences  $w^j \in V$ ,  $j = 0, \dots, n$ , such that:

$$(6) \quad i^j(w^j) = v_{n-j} \text{ and } \forall k = 0, \dots, j \quad i^k w^j \succeq_f v_{n-k}.$$

Observe that  $w^{(n)} := w^n$  will then have the required properties (i) and (ii) by eq. (6). (iii) will follow from the uniqueness of problem (6).

For  $j = 0$ , set  $w^0 = v_n$ . Assume that  $1 \leq j \leq n$  and that  $w^{j-1}$  has been defined satisfying (6). As  $v_{n-j} \rightsquigarrow v_{n-j+1}$ , there exist an integer  $l \geq 1$  and  $u \in i^{-1}(v_{n-j})$  such that  $u \succeq_f^l v_{n-j+1}$  (where, necessarily,  $l = |u| - |v_{n-j+1}| = |v_{n-j}| + 1 - |v_{n-j+1}|$ ). Hence there exists a  $w^j \in \mathcal{T}_i(u)$  which is the  $f^l$ -preimage of  $w^{j-1}$  in  $\mathcal{T}_i(v_{n-j+1})$  (recall that  $i^{j-1}(w^{j-1}) = v_{n-j+1}$ ).

Let us check (6) for  $w^j$ . Compute

$$|w^j| = l + |w^{j-1}| = |v_{n-j}| + 1 - |v_{n-j+1}| + (j - 1 + |v_{n-j+1}|) = |v_{n-j}| + j.$$

Thus,  $w^j \in \mathcal{T}_i(u)$  and  $i(u) = v_{n-j}$  (i.e.,  $w^j \in \mathcal{T}_i(v_{n-j})$ ) implying the first part of (6):

$$(7) \quad i^j(w^j) = v_{n-j}.$$

We now prove the second part. Observe that  $u \succeq_f^l v_{n-j+1}$ ,  $i^{j-1}(w^n) = u$ ,  $i^{j-1}(w^{j-1}) = v_{n-j+1}$  and  $f^l(w^j) = w^{j-1}$ . Hence Lemma 3.2 implies that, for  $0 \leq k \leq j-1$ ,  $i^k(w^j) \succeq_f^l i^k(w^{j-1})$ . Adding the second part of (6) for  $w^{j-1}$  we see that:

$$\forall 0 \leq k < j \quad i^k(w^j) \succeq_f i^k(w^{j-1}) \succeq_f v_{n-k}.$$

Thus eq. (6) holds for  $w^j$  and  $k < j$ . For  $k = j$ , this second part is just (7).

This completes the inductive construction of  $w^n$ .

For future reference, observe that  $w^j$  depends only on  $v_{n-j} \dots v_n$  and that the case  $k = 0$  of the previous equation gives:

$$(8) \quad w^j \succeq_f w^{j-1} \succeq_f v_n$$

Let us check the uniqueness of problem (6). We prove that for  $w^n$  satisfying eq. (6),  $i^{n-p}w^n$  is unique by an induction on  $0 \leq p \leq n$ . For  $p = 0$ , this is obvious. Assume it for  $p-1 \geq 0$ . Observe that  $i(i^{n-p}(w^n)) = i^{n-p+1}(w^n)$  and  $i^{n-p}(w^n) \succeq_f v_p$ . These two conditions uniquely determine  $i^{n-p}(w^n)$  according to Lemma 3.1. Thus  $w^n$  is indeed unique.

Thus we have shown the *existence* of  $w^{(n)}$  satisfying properties (i)-(iii) of the statement. We show that  $w^{(n)}$  is already unique under (i) and (ii). We proceed by induction on  $n$ . For  $n = 0$  this is obvious. Assume the uniqueness for  $n-1 \geq 0$ . Let  $w' := i(w^{(n)})$ . Observe that

- $i^{n-1}(w') = i^n(w^{(n)}) = v_0$ ;
- for  $0 \leq k < n$ ,  $i^k(w') = i^{k+1}(w^{(n)}) \succeq_f v_{n-k-1}$ , hence  $i^k(w') \succeq_f v_{n-1-k}$ .

By the induction hypothesis,  $w' = w^{(n-1)}$ . Thus  $i(w^{(n)}) = w^{(n-1)}$  and  $w^{(n)} \succeq_f v_n$  with  $v_n$  and  $w^{(n-1)}$  uniquely determined. Now, applying Lemma 3.1 completes the induction.

For the claim  $i(w^{(n+1)}) = w^{(n)}$ , observe that  $\omega := i(w^{(n+1)})$  satisfies  $i^n(\omega) = v_0$  and  $i^k\omega \succeq_f v_{n+1-k-1}$  for  $0 \leq k \leq n$ . Hence, the above uniqueness does imply that  $\omega = w^{(n)}$ , i.e.,  $i(w^{(n+1)}) = w^{(n)}$  as claimed.  $\square$

**Corollary 4.3.** *Let  $v \in \Sigma_+(\mathcal{D})$ . Then there exists a unique  $x \in X_V$  such that  $x_{|v_0|} = v_0$  and for all  $j \geq 0$ ,  $x_{|v_0|+j} \succeq_f v_j$ . Moreover  $x_{|v_0|+j}$  depends only on  $v_0 v_1 \dots v_j$ . For future reference we denote this  $x \in X_V$  by  $x(v)$ .*

PROOF: For each  $n \geq 0$ , apply the above proposition to the sequence  $v_0 \rightsquigarrow \dots \rightsquigarrow v_n$  to get  $w^n$ . As  $i(w^{n+1}) = w^n$ , the  $w^n$  define a sequence  $x$  in  $X_V$  by  $x_{|w^n|} = w^n$ . Moreover, for each  $n \geq 0$ ,  $x_{|w^n|-n+j} = i^{n-j}(w^n) \succeq_f v_j$ . As  $|w^n| = |v_0| + n$ , this implies that  $x_{|v_0|+j} \succeq_f v_j$ .

The uniqueness is proved by applying inductively Lemma 3.1 to  $i(x_{|v_0|+j+1}) = x_{|v_0|+j}$  and  $x_{|v_0|+j} \succeq_f v_j$ .

It is obvious that  $x_{|v_0|+j} = x_{|w^j|}$  depends only on  $v_0 \dots v_j$ .  $\square$

Let us define  $\pi : \Sigma_+(\mathcal{D}) \rightarrow X_V$  by:

$$\pi(\underline{v}) = F_V^{|\underline{v}_0|} \underline{x}$$

with  $\underline{x}$  as above.

**Lemma 4.4.** *The map  $\pi : \Sigma_+(\mathcal{D}) \rightarrow X_V$  is well-defined, continuous and satisfies:  $\pi \circ \sigma = F_V \circ \pi$ .*

PROOF: The above shows that  $\pi$  is indeed well-defined and continuous with values in  $X_V$ . We turn to the commutation relation.

We show that  $f((\pi v)_n) = (\pi \sigma v)_{n-1}$  for all  $n \geq 1$ . Denote by  $z^k$ , resp.  $w^k$ , the  $k$ th step result of the construction (6) for  $v_0 \rightsquigarrow \dots \rightsquigarrow v_n$ , resp.  $v_1 \rightsquigarrow \dots \rightsquigarrow v_n$  so that  $z^{n+1} = f((\pi v)_n)$  and  $w^n = (\pi \sigma v)_{n-1}$ .

Observe that  $z^k = w^k$  for  $k \leq n$  as they are both determined by  $v_{n-k} \dots v_n$ . Now  $\pi(v) = F_V^{|\underline{v}_0|} x$  with  $x_{|\underline{v}_0|+n} = z^{n+1}$  and  $\pi(\sigma(v)) = F_V^{|\underline{v}_1|} y$  with  $y_{|\underline{v}_1|+n-1} = w^n$ . By (8),  $z^{n+1} \succeq_f^\ell z^n = w^n$  with  $\ell = |z^{n+1}| - |z^n| = |\underline{v}_0| + 1 - |\underline{v}_1|$ . It follows that  $f^{|\underline{v}_0|+1-|\underline{v}_1|}(z^{n+1}) = w^n$ , hence:  $f(f^{|\underline{v}_0|} z^{n+1}) = f^{|\underline{v}_1|} w^n$ , implying the claim.  $\square$

**4.2. Partial conjugacy.** We are going to show that  $\pi$  gives an isomorphism between a subset of the natural extension  $\underline{X}_V$  of  $X_V$  and the whole of  $\Sigma(\mathcal{D})$ .

Observe that  $\pi : \Sigma_+(\mathcal{D}) \rightarrow X_V$  extends naturally to  $\pi : \Sigma(\mathcal{D}) \rightarrow \underline{X}_V$  by setting  $\pi(v) = x$  with  $x_{0p} x_{1p} \dots = \pi(v_p v_{p+1} \dots)$  because of the commutation in Lemma 4.4.

$x \in \underline{X}_V$  is *eventually Markovian* at time  $p$  if there exists  $0 \leq N < \infty$  such that:

$$\forall n \geq N \quad x_{n,p-n} \succeq_f x_{N,p-N}.$$

The *eventually Markovian subset*  $\underline{X}_V^M$  of  $\underline{X}_V$  is

$$\underline{X}_V^M = \{x \in \underline{X}_V : \forall p \in \mathbb{Z} \quad x \text{ is eventually Markovian at time } p\}$$

**Proposition 4.5.** *Define  $\iota : \underline{X}_V^M \rightarrow \Sigma(\mathcal{D})$  by  $\iota(x) = v$  if for all  $p \in \mathbb{Z}$ ,  $v_p$  is the irreducible vertex such that for all sufficiently large  $n$ :*

$$(9) \quad x_{n,p-n} \succeq_f v_p.$$

*Then  $\iota : (\underline{X}_V^M, F_V) \rightarrow (\Sigma(\mathcal{D}), \sigma)$  is well-defined and gives an isomorphism whose inverse is  $\pi$ .*

PROOF: Let us first check that  $\iota$  is well-defined with  $\iota(\underline{X}_V^M) \subset \Sigma(\mathcal{D})$ . Let  $x \in \underline{X}_V^M$ . Observe that by the definition of  $\underline{X}_V^M$ ,  $v = \iota(x)$  is well-defined as a unique element of  $\mathcal{D}^{\mathbb{Z}}$ . For an arbitrary  $p \in \mathbb{Z}$ , let us show that  $v_p \rightsquigarrow v_{p+1}$ . For  $n$  large enough,

$$(10) \quad \text{(i) } x_{n,p-n} \succeq_f^\ell v_p \text{ and (ii) } x_{n+1,p+1-n-1} = x_{n+1,p-n} \succeq_f^k v_{p+1}$$

where  $\ell = |x_{n,p-n}| - |v_p|$  and  $k = |x_{n+1,p-n}| - |v_{p+1}|$ . Let  $u = f^\ell(x_{n+1,p-n})$  (note that  $|x_{n+1,p-n}| = n+1 > n > \ell$ ).

We have  $i(u) = f^\ell(i(x_{n+1,p-n})) = f^\ell(x_{n,p-n}) = v_p$ . To see that  $u \succeq_f v_{p+1}$  (which will imply the claim  $v_p \rightsquigarrow v_{p+1}$ ), it is enough, by (10,ii), to show that  $\ell \leq k$ . But  $v_p \rightsquigarrow v_{p+1}$  implies  $0 \leq |v_p| - |v_{p+1}| + 1 = k - \ell$ , proving the claim. Thus,  $\iota$  is well-defined.

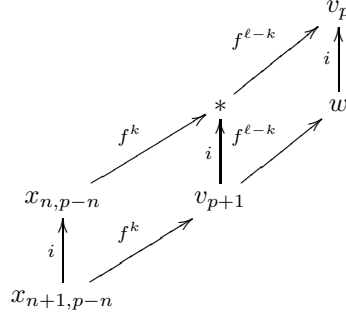


FIGURE 3. Construction of  $w^3$  from  $v_0 v_1 v_2 v_3$  as in Proposition 4.2.

Let us prove that  $\iota \circ \pi = \text{Id}_{\Sigma(\mathcal{D})}$ . Let  $v \in \Sigma(\mathcal{D})$  and  $x = \pi(v) \in \underline{X}_V$  by Lemma 4.4. Let us check that  $x$  belongs to  $\underline{X}_V^M$ . We have, for  $p \in \mathbb{Z}$  and  $n \geq 1$ ,

$$x_{n, p-n} = (\pi(v_{p-n} v_{p-n+1} \dots))_n = f^{|v_{p-n}|} (y_{|v_{p-n}|+n})$$

where  $y_{|v_{p-n}|+n} \succeq_f^k v_p$  for  $k = |v_{p-n}| + n - |v_p|$  by Corollary 4.3. For  $n \geq |v_p|$ ,  $k \geq |v_{p-n}|$  and this implies that

$$(11) \quad x_{n, p-n} = f^{|v_{p-n}|} (y_{|v_{p-n}|+n}) \succeq_f v_p.$$

Thus  $x$  is eventually Markov at any time  $p$ .  $x \in \underline{X}_V^M$  as claimed. Observe that eq. (11) also implies that  $\iota(x) = v$ , i.e.,  $\iota \circ \pi = \text{Id}_{\Sigma(\mathcal{D})}$  as claimed.

This shows that  $\iota : \underline{X}_V^M \rightarrow \Sigma(\mathcal{D})$  is onto. It remains to show that it is one-to-one. Let  $x, y \in \underline{X}_V^M$  with  $\iota(x) = \iota(y) =: v$ . Let  $p \in \mathbb{Z}$ . As  $v_p \rightsquigarrow v_{p+1}$ , there is a unique  $u_p^1$  such that  $i(u_p^1) = v_p$  and  $u_p^1 \succeq_f^k v_{p+1}$  for  $k = |v_p| + 1 - |v_{p+1}|$  by Lemma 3.1.

We claim that  $u_p^1 \rightsquigarrow u_{p+1}^1$ . Indeed,  $u_p^1 \succeq_f v_{p+1}$  implies that  $f^k : \mathcal{T}_i(u_p^1) \rightarrow \mathcal{T}_i(v_{p+1})$  is an isomorphism so that there exists  $w \in \mathcal{T}_i(u_p^1)$  with  $f^k(w) = u_{p+1}^1$ . Lemma 3.2 gives then that  $w \succeq_f u_{p+1}^1$ . But this says that  $u_p^1 \rightsquigarrow u_{p+1}^1$ , as claimed.

This claim allows us to repeat the previous construction with  $u_p^1$  instead of  $v_p$ , obtaining sequences  $u^2, u^3, \dots$

We now show that these sequences determine  $x$  and  $y$  and thus force them to coincide.

For  $n$  large enough, we have  $x_{n, p-n}, y_{n, p-n} \succeq_f^\ell v_p$  for  $\ell = n - |v_p|$  and  $x_{n+1, p-n}, y_{n+1, p-n} \succeq_f v_{p+1}$ . Then  $x_{n+1, p-n} \succeq_f^\ell x_{n+1-\ell, p-n+\ell+1} =: w$  and  $w$  must satisfy  $i(w) = v_p$  and  $w \succeq_f v_{p+1}$  (observe that  $|w| = n + 1 - \ell = |v_p| + 1 \geq |v_{p+1}|$ ). Thus

$$x_{n+1, p-n}, y_{n+1, p-n} \succeq_f w = u_p^1 = x_{|v_p|+1, p-|v_p|+1} = y_{|v_p|+1, p-|v_p|+1}.$$

In particular,  $\iota(\sigma x) = \iota(\sigma y) = u^1$ .

Thus we can repeat this analysis with  $u_p^1$  instead of  $v_p$  we get:

$$u_p^j = x_{|v_p|+j, p-|v_p|+1} = y_{|v_p|+j, p-|v_p|+1}$$

As  $|u_p^j| \geq j \rightarrow \infty$ , we obtain  $x = y$ . □

**Corollary 4.6.** *The induced maps on the invariant probability measures  $\pi : \text{Prob}(\sigma, \Sigma(\mathcal{D})) \rightarrow \text{Prob}(F_V, \underline{X}_V)$  and  $\pi : \text{Prob}(\sigma, \Sigma_+(\mathcal{D})) \rightarrow \text{Prob}(F_V, X_V)$  are one-to-one and preserves ergodicity and entropy.*

PROOF: That  $\pi : \Sigma(\mathcal{D}) \rightarrow \underline{X}_V$  is a partial isomorphism trivially implies the stated properties of  $\pi : \text{Prob}(\sigma, \Sigma(\mathcal{D})) \rightarrow \text{Prob}(F_V, \underline{X}_V)$ . To finish, recall that the natural extension construction preserves ergodicity and entropy,  $\square$

**Corollary 4.7.** *The map  $\pi : \Sigma_+(\mathcal{D}) \rightarrow X_V$  is at most countable-to-one almost everywhere w.r.t. any invariant probability measure on  $\Sigma_+(\mathcal{D})$ .*

PROOF: By Poincaré recurrence, for a.e.  $v \in \Sigma_+(\mathcal{D})$ ,  $L_v := \liminf_{p \rightarrow \infty} |v_p| < \infty$ . Hence, there exist  $p_v \geq L_v$  such that  $|v_{p_v}| = L_v$ . Now, for  $p \geq p_v$ ,  $|v_p| \leq L + (p - p_v)$  so (9) implies that, writing  $x := \pi(v)$ ,  $v_p = f^k(x_{|v_p|, p - |v_p|})$  and  $p - |v_p| \geq p_v - L \geq 0$ . Therefore  $x = \pi(v)$ ,  $p_v$  and  $v_0, \dots, v_{p_v}$  determine  $v$ . As there are countably many choices of the finitely many vertices  $v_0, \dots, v_{p_v}$ , the corollary is proved.  $\square$

### 4.3. Entropy of the non-Markov part.

**Proposition 4.8.** *If  $\mu$  is an invariant and probability measure with  $\mu(\underline{X}_V \setminus \underline{X}_V^M) = 0$ , then*

$$h(F_V, \mu) \leq h_C(V).$$

**Lemma 4.9.** *Up to a set of zero measure with respect to any invariant probability measure, each  $x \in \underline{X}_V \setminus \underline{X}_V^M$  satisfies: for all  $p \in \mathbb{Z}$  there exist arbitrarily large integers  $n$  such that  $x_{n, p-n}$  does not  $f$ -reduce, i.e., it is an  $f$ -irreducible vertex.*

PROOF OF THE LEMMA: By definition  $x \in \underline{X}_V \setminus \underline{X}_V^M$  iff there exists  $p \in \mathbb{Z}$  as in the statement of the Lemma. Let  $X(p)$  be the set of such  $x$ . The lemma is clearly equivalent to the fact that, for any invariant probability  $\mu$ ,

$$(12) \quad \mu \left( \bigcup_{p \in \mathbb{Z}} X(p) \right) = \mu \left( \bigcap_{p \in \mathbb{Z}} X(p) \right).$$

It is enough to prove this for ergodic  $\mu$ 's such that the union has positive and hence full measure. If we prove that  $X(p+1) \subset X(p)$ , it will follow that  $\mu \left( \bigcup_{p \in \mathbb{Z}} X(p) \right) = \lim_{p \rightarrow \infty} \mu(X(p))$  which is equal to  $\mu(X(p))$  for any  $p \in \mathbb{Z}$  by invariance of  $\mu$ , proving (12). But observe that by Lemma 3.2

$$x_{n, p-n} \succeq_f x_{N, p-N} \implies x_{n+1, p+1-(n+1)} \succeq_f x_{N+1, p+1-(N+1)}$$

so that  $x \notin X(p) \implies x \notin X(p+1)$ , which concludes the proof.  $\square$

Recall that the entropy of an invariant and ergodic probability measure  $\mu$  can be computed as [20]:

$$h(F_V, \mu) = \lim_{\epsilon \rightarrow 0} h(F_V, \mu, \epsilon) \text{ with}$$

$$h(F_V, \mu, \epsilon) = \limsup_{n \rightarrow \infty} \frac{1}{n} \log \min \left\{ \#S : \mu \left( \bigcup_{x \in S} B(x, \epsilon, n) \right) > \mu_0 \right\}.$$

where  $0 < \mu_0 < 1$  is arbitrary.

PROOF OF THE PROPOSITION: Let  $\mu$  be an invariant probability measure carried by  $\underline{X}_V \setminus \underline{X}_V^M$ . We may and do assume that  $\mu$  is ergodic. Let  $\alpha > 0$  be arbitrarily small. There exists  $r > 0$  (depending on  $\mu$ ) so that  $h(F_V, \mu) \leq h(F_V, \mu, r) + \alpha$ . Fix  $L_1 < \infty$  and  $r_1 > 0$  such that for  $x, y \in \underline{X}_V$ ,  $d(x_{2L_1, -L_1}, y_{2L_1, -L_1}) < r_1 \implies d(x, y) < r$  (for any distances on  $X_V$  and  $\underline{X}_V$  compatible with the topologies). Let  $L_2$  such that  $r(r_1, n, \mathcal{C}_n) \leq e^{(h_C(V) + \alpha)n}$  for all  $n \geq L_2$  and fix, for each such  $n$ , some  $(r_1, n)$ -cover<sup>3</sup>  $C_n$  of  $\mathcal{C}_n$  with this minimum cardinality. For each  $v \in C_n$ , we pick some  $x = x^v \in \underline{X}_V$  such that  $x_{n,0}^v = v$  and let  $X_n := \{x^v \in X_V : v \in C_n\}$ .

Let  $L \gg L_1 \log K / \alpha + L_2$  where  $K$  is the minimum cardinality of an  $r$ -dense subset of  $\underline{X}_V$ . It follows from Lemma 4.9 that there exists a measurable function  $n : \underline{X}_V \rightarrow \mathbb{N}$  such that, for  $\mu$ -a.e.  $\underline{x} \in \underline{X}_V$ :

- $n(\underline{x}) \geq L$ ;
- $x_{n,-n}$  is  $f$ -irreducible for  $n = n(\underline{x})$ .

Hence (see [8]) a  $\mu$ -typical  $x$  satisfies the following. For all large  $n$ , there exist disjoint integer intervals  $[a_i, b_i] \subset [0, n]$ ,  $i = 1, \dots, r$ , such that

- (1)  $\sum_{i=1}^r b_i - a_i \geq (1 - \alpha)n$ ;
- (2)  $b_i - a_i \geq L$  for all  $i = 1, \dots, r$ ;
- (3)  $x_{b_i - a_i + 1, a_i} \not\sim_f x_{b_i - a_i, a_i + 1}$ : in particular,  $x_{b_i - a_i + 1, a_i}$  is  $f$ -irreducible. Thus  $F_V^{a_i + L_1}(x) \in B(y, r, b_i - a_i - 2L_i)$  for some  $y \in X_{b_i - a_i + 1}$ .

It follows in a standard fashion (see, e.g., again [8]) that  $h(F_V, \mu) \leq h_C(V) + 5\alpha + 2 \log \alpha$ . Letting  $\alpha$  decrease to zero concludes the proof.  $\square$

#### 4.4. Entropy at infinity in the diagram.

**Proposition 4.10.** *Let  $H > h_C(V) + h_{\text{wloc}}(V)$ . Then there exist a finite subset  $\mathcal{D}_0 \subset \mathcal{D}$  such that:*

$$h(\mathcal{D} \setminus \mathcal{D}_0, \mathcal{D}) := \inf_{\mu_0 > 0} \sup \left\{ h(\sigma, \mu) : \mu \in \text{Prob}_{\text{erg}}(\Sigma(\mathcal{D})) \text{ and } \mu \left( \bigcup_{D \in \mathcal{D}_0} [D] \right) < \mu_0 \right\} \leq H$$

where  $\text{Prob}_{\text{erg}}(\Sigma(\mathcal{D}))$  is the set of shift-invariant and ergodic probability measures on  $\Sigma(\mathcal{D})$ .

PROOF: We have to find  $\mathcal{D}_0$  and  $\mu_0 > 0$  such that if  $\mu \in \text{Prob}_{\text{erg}}(\Sigma(\mathcal{D}))$  such that

$$(13) \quad \mu \left( \bigcup_{D \in \mathcal{D}_0} [D] \right) < \mu_0,$$

then  $h(\sigma, \mu) \leq H$ .

Let  $\alpha > 0$  be so small that  $h_C(V) + h_{\text{wloc}}(V) + 3|\log \alpha| \leq H$ . Let  $r > 0$  be such that  $h_{\text{wloc}}(F_V, r) \leq h_{\text{wloc}}(F_V) + \alpha$  (the point here is that  $r$  is independent of the invariant measure —compare with Proposition 4.5). Fix  $L_1 < \infty$  and  $r_1 > 0$  such that, for all  $x, y \in \underline{X}_V$ ,  $d(x_{2L_1, -L_1}, y_{2L_1, -L_1}) < r_1 \implies d(\underline{x}, \underline{y}) < r$ . We increase  $L_1$  if necessary so that  $L_1 > r_1^{-1}$ . Recall that  $\mathcal{C} = (C_n)_{n \geq 1}$  with  $C_n$  the set of irreducible vertices of order  $n$ . Let  $L_2$  such that  $r(r_1, n, \mathcal{C}) \leq e^{(h_{\text{top}}(\mathcal{C}) + \alpha)n}$  for all  $n \geq L_2$ . Let  $K$  be the cardinality of a finite  $r$ -dense subset of  $\underline{X}_V$  and let  $L > \alpha^{-1} L_1 \log K + L_2$ .

Finally let

$$\mathcal{D}_0 = \{v \in \mathcal{D} : |v| \leq L\}$$

<sup>3</sup>Here,  $(r, n)$ -cover is in the sense used to define the entropy of sequences.

and let  $\mu_0 > 0$  be a very small number to be specified later.

Let  $\mu$  be an ergodic invariant probability measure on  $\Sigma(\mathcal{D})$  satisfying (13). We bound  $h(\sigma, \mu)$ . First observe that by Corollary 4.6,  $h(\sigma, \mu) = h(F_V, \pi_*\mu)$ . Let  $x \in \underline{X}_V$  be a  $\pi_*\mu$ -typical point. Thus  $x = \pi(v)$  with  $v$  a path on  $\mathcal{D}$  spending a fraction of its time less than  $\mu_0$  in  $\mathcal{D}_0$ .

This implies that there exists disjoint integer intervals  $[a_1, b_1), \dots \subset [0, n)$  and vertices  $v_1, \dots \in \mathcal{D} \setminus \mathcal{D}_0$  such that  $\sum_i b_i - a_i \geq (1 - \mu_0)n$ ,  $d(x_{a_i+k}, f^k(v_i)) < r_1$  for all  $k \in [0, b_i - a_i - L_1)$ . Note that the  $b_i - a_i$  are large (larger than  $L$ ). By definition of  $\mathcal{D}$ , the  $v_i$ s are  $f$ -irreducible. It follows as in the proof of Proposition 4.8 that

$$h(F_V, \pi_*\mu, r) \leq h_C(V) + 4\alpha + 2|\log \alpha| + \mu_0 \log K \leq h_C(V) + 3|\log \alpha|$$

if  $\mu_0 = \mu_0(V, r, \alpha)$  is small enough. Thus,

$$h(F_V, \pi_*\mu) \leq h_C(V) + h_{\text{wloc}}(F_V, r) + 3|\log \alpha| \leq H,$$

proving the proposition.  $\square$

**4.5. Conclusion of the Analysis of Large Entropy Measures.** We collect all the partial results and check that they imply the first two claims of Theorem 1.

Let first  $V$  be a \*-QFT puzzle. Propositions 4.5 and 4.8 immediately imply that  $\underline{X}_V$  is entropy-conjugate with constant  $h_C(V)$  to the Markov shift,  $\Sigma(\mathcal{D})$ , proving the first claim of the Theorem.

We assume that  $V$  is QFT :  $h_{\text{top}}(X_V) > H_* := h_C(V) + h_{\text{wloc}}(X_V)$ . Proposition 4.10 implies that  $h_\infty(\mathcal{D}) \leq H_*$ .

Take  $H$  strictly between  $H_*$  and  $h_{\text{top}}(V)$ :  $\mathcal{D}$  contains only finitely many irreducible Markov subshifts  $S$  with entropy  $h(S) \geq H$ . This implies that  $h(S) > H_* \geq h_\infty(\mathcal{D}) \geq h_\infty(S)$ . Hence, by the result of Gurevič and Zargaryan [15] quoted in Proposition 6.1 below these irreducible subshifts are SPR. This proves claim (2) of Theorem 1.

## 5. PERIODIC STRUCTURE

In this section we prove Claim (3) of Theorem 1 which relates most periodic orbits in the Markov shift with most periodic orbits in some fine scale approximation  $i_N(X_V)$  of the puzzle dynamics  $X_V$ .

**5.1. Partition of the periodic points.** The construction will use two integer parameters  $N, L \geq 1$  depending on  $\epsilon > 0$ . We shall denote  $i_N \circ \pi : \Sigma(\mathcal{D}) \rightarrow i_N(\underline{X}_V)$  by  $\pi_N$ . The  $n$ -fixed points  $\xi = F_V^n \xi$  of  $i_N(X_V)$  fall into three disjoint categories:

- (P1) there exist  $v \in \pi_N^{-1}(\xi) \in \Sigma(\mathcal{D})$  such that  $I_N(v) := \{p \geq 0 : |v_p| < N\}$  is infinite.
- (P2)  $\pi_N^{-1}(\xi) \neq \emptyset$  but for all  $v$  in this set,  $I_N(v)$  is finite.
- (P3)  $\pi_N^{-1}(\xi) = \emptyset$ .

Denote by  $\widehat{\text{Fix}}_i(n)$ ,  $i = 1, 2, 3, 4$ , the corresponding set of periodic points of  $i_N(X_V)$ .

On the other hand, we consider on the Markov shift only the periodic points defined by *low loops*:

$$\widehat{\text{Fix}}_1(n) := \{v \in \Sigma(\mathcal{D}) : \sigma^n v = v \text{ and } \{v_0, \dots, v_{n-1}\} \cap \mathcal{D}_N \neq \emptyset\}.$$

We shall say nothing about the others.



**5.2. Low loops and periodic points of  $i_N(X_V)$ .** Let  $\epsilon > 0$ ,  $N_0$  and  $\mathcal{D}_0$  be given as in the statement of the Theorem. Fix  $N \geq N_0$  so that  $\mathcal{D}_N \supset \mathcal{D}_0$  and  $h(\mathcal{D} \setminus \mathcal{D}_N) \leq h_C(V) + h_{\text{wloc}}(V) + \epsilon$  (which is possible by Proposition 4.10 as  $h(\mathcal{D} \setminus \mathcal{D}_N) \leq h(\mathcal{D} \setminus \mathcal{D}_N, \mathcal{D})$ ).

We first claim that for all  $n \geq 1$ :

$$(14) \quad \#\widetilde{\text{Fix}}_1(n) = \#\widehat{\text{Fix}}_1(n)$$

We need the following consequence of determinacy:

**Lemma 5.1.** *Let  $V$  be a determined puzzle and  $N \geq 1$ . Let  $v, v' \in \Sigma(\mathcal{D})$ . If  $x = \pi(v)$  and  $x' = \pi(v')$  satisfy  $i_1(x) = i_1(x')$ , then:*

$$(15) \quad v_0 = v'_0 \implies \forall n \geq 0 \ x_{n,-n} = x'_{n,-n}$$

PROOF: For  $n = n_0 := |v_0|$ , the right hand side of (15) follows from  $v_0 = x_{n_0,-n_0} = x'_{n_0,-n_0}$ , which holds by (9). This implies (15) for  $n \leq n_0$ . Assuming it for some  $n \geq n_0$ , (9) again implies  $x_{n+1,-n-1}, x'_{n+1,-n-1} \succeq_f x_{n,-n} = x'_{n,-n}$ . Together with the determinacy and  $i_1(x_{n+1,-n-1}) = i_1(x'_{n+1,-n-1})$ , this completes the induction and the proof of the lemma.  $\square$

We deduce (14) from this Lemma. Let

$$\Sigma(N) := \{v \in \Sigma(\mathcal{D}) : \exists p \rightarrow \infty \ |v_p| < N\}$$

By Lemma 5.1,  $\pi_N|_{\Sigma(N)}$  is one-to-one.  $\widetilde{\text{Fix}}_1(n)$  is by definition the set of fixed points  $\xi$  of  $\sigma^n$  in  $\pi_N(\Sigma(N))$ . By the injectivity of  $\pi_N|_{\Sigma(N)}$  and the  $\sigma$ -invariance of  $\Sigma(N)$ , such  $\xi$  are the  $\pi_N$  images of the fixed points of  $\sigma^n$  in  $\pi_N(\Sigma(N))$ . This proves the claim (14).

**5.3. Remaining loops and periodic points.** Second, we shall see that the remaining factors are holomorphic:

**Lemma 5.2.** *For every  $\epsilon > 0$ , for all  $n \geq 1$ :*

$$(16) \quad \#\widetilde{\text{Fix}}_2(n) \leq C(N, \epsilon)e^{(h_C(V) + \epsilon)n}$$

$$(17) \quad \#\widetilde{\text{Fix}}_3(n) \leq C(N, \epsilon)e^{(h_C(V) + \epsilon)n}.$$

*Remark.* Of course,  $L$  being large,  $h(\Sigma(\mathcal{D} \setminus \mathcal{D}_N)) < H := h_C(V) + h_{\text{wloc}}(V) + \epsilon < h_{\text{top}}(V)$  but this is insufficient to prove (16) as Gurevič entropy only controls the number of loops based at a *fixed* vertex. Indeed, in some examples,  $\mathcal{D} \setminus \mathcal{D}_N$  contains infinitely many loops of each length.

This Lemma will be enough to conclude the proof of Theorem 3.

**5.4. Paths above  $N$ .** To prove (16) we bound the number of the  $n$ -periodic projections to  $i_N(X_V)$  of (not necessarily periodic) paths on  $\mathcal{D} \setminus \mathcal{D}_N$ .

The proof is similar to that of Proposition 4.10. For  $n \geq N$ , let

$$(18) \quad C(n) := \left\{ (i_N(v), i_N(f(v)), \dots, i_N(f^{n-N}(v))) \in V_{\leq N}^{n-N} : \right. \\ \left. v \in V_n \text{ and } v \text{ is irreducible} \right\}$$

By (9), for all  $w \in \Sigma(\mathcal{D})$ , writing  $y := \pi(w) \in \underline{X}_V$ ,  
(19)

$$w_0 \text{ irreducible with } \ell := |w_0| \geq N \implies (y_{N,-\ell+1}, y_{N,-\ell+2}, \dots, y_{N,-N}) \in C(\ell)$$

so that  $\{C(n) : n \geq 1\}$  controls the projections of high paths. By the definition of  $h_C(V)$ ,  $\#C(n) \leq C(N, \epsilon)e^{(h_C(V)+\epsilon)n}$ , hence this control should give the right entropy bound. Let us see the details (the bound proved below is only  $h_C(V) + h_{\text{wloc}}(V)$ ). We fix  $L = L(N, \epsilon)$ , a large integer.

Let  $n \geq 1$  and  $\xi \in i_N(\underline{X}_V)$  with  $\sigma^n \xi$  satisfying (P1):  $\xi = \pi(v)$  for some  $v \in \Sigma(\mathcal{D})$  satisfying:  $|v_p| \geq N$  for all  $p \geq p_0$ . By periodicity of  $\xi$ , we can assume  $p_0 = 0$  by shifting  $v$  a multiple of the period. We shift again  $\xi$  to ensure  $I_L(v) = \emptyset$  if  $I_L(v)$  is finite,  $|v_0| \leq L$  otherwise (this might produce an irrelevant factor  $n$  in the estimates). Let  $x = \pi(v) \in \underline{X}_V$ .

Define inductively the integers  $r \geq 1, n > b_1 > \dots > b_r \geq 0$  as follows.  $b_1 := n - 1$ . If  $b_i$  is defined,  $b_i \geq 0$  and  $|v_{b_i}| > L$ , then  $b_{i-1} := b_i - |v_{b_i}|$ , otherwise let  $r := i - 1$ . Finally set  $\ell_i := |v_{b_i}|$  for all  $i = 1, 2, \dots, r$ .

Now, by (19),  $x_{N, b_i - \ell_i + k} = i_N \circ f^k(v_{b_i})$  for  $0 \leq k < \ell_i - N$ . Thus, there exists  $x_i \in C(\ell_i)$ , such that  $\xi_{b_i - \ell_i + k} = (x(i))_k$  for  $0 \leq k \leq \ell_i - N$ .

Notice that  $\ell_i \geq L$  for  $i = 1, \dots, r$ . Hence, given  $n \geq 1$  and  $b_r$ , when  $v$  ranges over  $\Sigma(\mathcal{D} \setminus \mathcal{D}_N)$ , the number of choices for the integers  $b_1, \dots, b_{r-1}$  is at most  $e^{\epsilon(n-b_r)}$  as  $L$  is large. This implies a bound of the type:

$$(20) \quad \#\{\xi_{b_r} \dots \xi_{n-1} : \xi \in \widetilde{\text{Fix}}_2(n) \text{ with given } b_r\} \leq \\ Cn(\#V_{\leq N})^{N(n-b_r)/L} \cdot e^{\epsilon(n-b_r)} \cdot C(N, \epsilon)^{(n-b_r)/L} \exp(h_C(V) + \epsilon)(n - b_r) \\ \leq C e^{(h_C(V)+3\epsilon)(n-b_r)}$$

using that  $L = L(N, \epsilon)$  is large. Note that there are at most  $n$  possibilities for  $b_r$ .

There are two cases. First case:  $|v_{b_r}| \leq L$ . Let  $\widetilde{\text{Fix}}_2^{(1)}(n)$  be the corresponding subset of  $\widetilde{\text{Fix}}_2(n)$ .  $v_0 \dots v_{b_r}$  is a path on  $\mathcal{D} \setminus \mathcal{D}_N$  which starts and ends in the finite subgraph  $\mathcal{D}_L \setminus \mathcal{D}_N$ . Using Gurevič entropy, we obtain:

$$\#\widetilde{\text{Fix}}_2^{(1)}(n) \leq n(\#\mathcal{D}_L \setminus \mathcal{D}_N)^2 \sum_{b_r} e^{(h(\mathcal{D} \setminus \mathcal{D}_N) + \epsilon)b_r} \times C e^{(h_C(V) + 3\epsilon)(n-b_r)} \\ \leq C e^{(h_C(V) + h_{\text{wloc}}(V) + 4\epsilon)n}$$

Second case:  $|v_{b_r}| > L$  and  $b_r - |v_{b_r}| =: -\delta < 0$ . Let  $\widetilde{\text{Fix}}_2^{(2)}(n)$  be the corresponding subset of  $\widetilde{\text{Fix}}_2(n)$ . We shift  $\xi$  by  $\delta$  (and add  $\delta$  to each  $b_i$ ) so  $b_r - |v_{b_r}| = 0$  (doing this we lose the property  $|v_0| \leq L$  if  $I_L(v)$  is infinite but not the (irrelevant) factor  $n$ ). Of course,  $b_1, \dots, b_s \geq n$  for some (maximum)  $s \geq 1$ . We forget about  $b_1, \dots, b_{s-1}$  and we trim  $v_{b_s}$  in the following way. We replace  $b_s, v_{b_s}$  and  $\ell_s$  by  $n - 1, v_* := i^{b_s - n + 1}(v_{b_s})$  and  $\ell_* := \ell_s - (b_s - n + 1)$ . We have now that  $x_{-N, b_s - \ell_s + i} = i_N(f^i v_*)$  for  $0 \leq i < \ell_* - N$ . We now proceed as in (20) and obtain:

$$\widetilde{\text{Fix}}_2^{(2)}(n) \leq C e^{\epsilon n} n(\#V_N)^{N(n/L+1)} \cdot C(N, \epsilon)^{n/L+1} \exp(h_C(V) + \epsilon)n \leq C e^{(h_C(V) + 3\epsilon)n}$$

This concludes the proof of (16).

**5.5. Unliftable periodic orbits.** Let  $\xi \in \widetilde{\text{Fix}}_3(n)$ . By definition, for any  $x \in \underline{X}_V$  projecting to  $\xi$ , there exist  $p \in \mathbb{Z}$  and arbitrarily large integers  $k$  such that,  $x_{k, p-k}$

is  $f$ -irreducible. Take such an integer  $k \geq N + n$  and observe that  $v_* := x_{N+n, p-k}$  is  $f$ -irreducible by Lemma 3.2. Hence, setting  $q := p - k - |v_*|$ ,

$$\xi_{q+i} = i_N(f^i(v_*)) \text{ for all } 0 \leq i < n$$

This implies that

$$\#\widetilde{\text{Fix}}_3(n) \leq C(N, \epsilon) e^{(h_C(V) + \epsilon)n}$$

proving eq. (17) and concluding the proof of Theorem 3.

## 6. SEMI-LOCAL ZETA FUNCTIONS OF SPR MARKOV SHIFTS

We give a proof of Theorem 4 about the meromorphy of the semi-local zeta functions of SPR Markov shifts, after recalling the relation between the entropy at infinity and the SPR property.

**6.1. SPR property and entropy at infinity.** A combinatorial quantity related to  $h_\infty(G)$  appearing in our result appear in a work of Gurevič-Zargaryan [15] to give a sufficient condition for being SPR, which was then shown to be necessary (see [14, Theorem 3.8]). The explicit relation (21) below is due to Ruelle [30].

**Proposition 6.1** (Gurevič-Zargaryan, Gurevič-Savchenko, Ruelle). *Let  $G$  be a countable, oriented, irreducible graph with  $h(G) < \infty$ . The graph  $G$  is SPR iff  $h_\infty(G) < h(G)$  where the entropy at infinity  $h_\infty(G)$  has been defined in 1 and can be computed as:*

$$(21) \quad h_\infty(G) = \inf_{F \subset\subset G} \max_{u, v \in F} \limsup_{n \rightarrow \infty} \frac{1}{n} \log \#\{(x_0, \dots, x_n) \in \{u\} \times G^{n-1} \times \{v\} : \\ \forall i = 0, \dots, n \ x_i \rightarrow x_{i+1} \text{ on } G \text{ and } \{x_1, x_2, \dots, x_{n-1}\} \cap F = \emptyset\}$$

where  $F \subset\subset G$  means that  $F$  ranges over the finite subgraphs of  $G$ .

Observe that by this proposition, the conclusion of our Theorem 4 is non-trivial iff the Markov shift is SPR.

**6.2. Semi-local zeta function of large subsets.** The first step of the proof of Theorem 4 is the following weaker claim on semi-local zeta functions defined by large subgraphs:

**Claim 6.2.** *For every  $\epsilon > 0$ , there exists a finite subset  $F_0 \subset\subset G$  such that for all finite subsets  $F_0 \subset F \subset\subset G$ , the semi-local zeta function  $\zeta_F^G(z)$  extends meromorphically to  $|z| < \exp -h_\infty(G) - \epsilon$ .*

The crux of the proof is to check that

$$\zeta_F^G(z) = 1 / \det(I - M(z))$$

with  $M(z)$  a finite matrix with holomorphic entries for  $|z| < e^{-h_\infty(G) - \epsilon}$ . It is inspired by [17] and especially by their use of the following formula for a block decomposition  $A, U, V, B$  of a finite matrix such that  $B$  is invertible:

$$\det \begin{pmatrix} A & U \\ V & B \end{pmatrix} = \det B \det(A - UB^{-1}V).$$

This formula is proved algebraically. But it has a combinatorial interpretation for incidence matrices as a splitting between periodic sequences going through the indices of  $A$  and the others, as we shall see for infinite matrices.

PROOF OF CLAIM 6.2: Let  $\epsilon > 0$  and fix a finite subgraph  $F_0 \subset\subset G$  such that  $h(G \setminus F_0, G) < h_\infty(G) + \epsilon$ , hence, for all  $u, v \in F_0$ :

$$\limsup_{n \rightarrow \infty} \frac{1}{n} \log \#\{x_1 \cdots \rightarrow x_{n-1} : x \in \Sigma(G) \text{ s.t.}$$

$$x_0 = u, x_n = v, \text{ and } \{x_1, x_2, \dots, x_{n-1}\} \cap F = \emptyset\} < h_\infty(G) + \epsilon.$$

This trivially holds for all larger (but finite)  $F \subset G$ . Let  $K : G \times G \rightarrow \{0, 1\}$  be the adjacency matrix of  $G$  and let  $K = \begin{pmatrix} A & U \\ V & B \end{pmatrix}$  be the decomposition associated to  $G = F \cup F^c$ . Consider:

$$Z(z) := \sum_{r \geq 1} \frac{1}{r} \text{Tr} \left( zA + \sum_{i \geq 0} zU \cdot z^i B^i \cdot zV \right)^r.$$

Observe that the coefficient of  $z^n$  in  $\text{Tr} \left( zA + \sum_{i \geq 0} zU \cdot z^i B^i \cdot zV \right)^r$  is the number of sequences  $x \in \Sigma(G)$  with  $x_0 \in F$ ,  $x = \sigma^n x$ ,  $S := \{k = 0, \dots, n-1 : x_k \in F\}$  has cardinality  $r$ .

For such an  $x \in \Sigma(G)$ , let  $\mathcal{O}(x) := \{\sigma^n x : n \in \mathbb{Z}\}$ ,  $d(x) := \#\mathcal{O}(x)$  be the minimal period and  $\tilde{S}(x) := S \cap [0, d-1]$ . Let  $t(n, d, \tilde{S})$  be the number of such  $x$  with given  $n$ ,  $d$  and  $\tilde{S}$ . Hence

$$\frac{1}{r} \text{Tr} \left( zA + \sum_{i \geq 0} zU \cdot z^i B^i \cdot zV \right)^r = \sum_{n \geq 1} \frac{z^n}{r} \sum_{\substack{d|n \\ \frac{n}{d} | r}} \sum_{\substack{\tilde{S} \subset [0, d-1] \\ 0 \in \tilde{S} \\ \tilde{S} = r/(n/d)}} t(n, d, \tilde{S})$$

Summing over  $r \geq 1$ , we get that:

$$(22) \quad Z(z) = \sum_{n \geq 1} z^n \sum_{d|n} \sum_{\substack{\tilde{S} \subset [0, d-1] \\ 0 \in \tilde{S}}} \frac{t(n, d, \tilde{S}) d}{\#\tilde{S} n}.$$

Now, let  $O_F(d) := \{x \in \Sigma : \#\mathcal{O}(x) = d \text{ and } \{x_0, \dots, x_{d-1}\} \cap F \neq \emptyset\}$  and further partition  $O_F(d)$  into  $O_F(d, \tilde{S}/\equiv)$  according to  $\tilde{S}(x) := \{k : x_k \in F\}$  up to a translation ( $\tilde{S} \equiv \tilde{T}$  iff  $\tilde{S} = \tilde{T} + q$  in  $\mathbb{Z}/d\mathbb{Z}$  for some integer  $q$ ).

Each periodic orbit in  $O_F(d, \tilde{S}/\equiv)$  ( $\emptyset \neq \tilde{S} \subset \mathbb{Z}/d\mathbb{Z}$ ) gives  $\#\tilde{S}$  distinct points  $x = \sigma^n x$  with  $x_0 \in F$  for each  $p \geq 1$  ( $n = pd$ ). The translated  $\tilde{S}$  may be distinct or not. Nevertheless, each periodic orbit in  $O_F(d, \tilde{S}/\equiv)$  contributes  $\#\tilde{S}$  to the sum of  $t(pd, d, \tilde{S})$  over all  $\tilde{S}$ . Therefore:<sup>4</sup>

$$Z(z) = \sum_{d \geq 1} \sum_{\tilde{S}/\equiv} \sum_{p \geq 1} \frac{\#\tilde{S} \cdot \#O_F(d, \tilde{S}/\equiv)}{p \#\tilde{S}} z^{pd} = \sum_{d \geq 1} \sum_{p \geq 1} \frac{z^{pd}}{pd} d \#O_F(d) = \sum_{n \geq 1} \frac{z^n}{n} \sum_{d|n} d \#O_F(d)$$

Obviously, each orbit in  $O_F(d)$  corresponds to  $d$  distinct fixed points  $x = \sigma^n x$  with  $\{x_0, \dots, x_n\} \cap F \neq \emptyset$ . Hence, the above implies:

$$\exp Z(z) = \zeta_F^G(z)$$

<sup>4</sup>The notation  $\equiv$  on the first summation symbol stresses that this summation is over  $S \subset \mathbb{Z}/d\mathbb{Z}$  up to translation.

(an equality between formal series). Now, if  $Q$  is a finite square matrix with spectral radius  $< 1$ ,

$$\det(I - Q) = \exp \operatorname{Tr} \log(I - Q) = \exp - \sum_{r \geq 1} \frac{z^r}{r} \operatorname{Tr}(Q^r)$$

Hence, at least for small  $z$  (therefore as formal series):

$$\exp -Z(z) = \det(I - zA - M(z))$$

where  $M$  is the finite  $F \times F$ -matrix defined by:

$$M(z) = \sum_{n \geq 0} zU \cdot z^n B^n \cdot zV.$$

$M(z)$  is a holomorphic function of  $z$  for  $|z| < e^{-h_\infty(G) - \epsilon}$  with  $\epsilon = \epsilon(F) > 0$ . Indeed, its (finitely many) coefficients are just power series in the numbers of paths on  $F^c$  of length  $n$  between all the couples of vertices (in  $F$ ). Hence these coefficients are bounded by  $C(\epsilon, F)e^{(h_\infty(G) + \epsilon)n}$  as  $F \supset F_0$ . This proves the meromorphy over  $|z| < \exp -h_\infty(G) - \epsilon$ .  $\square$

**6.3. Proof of Theorem 4.** Claim 6.2 shows the meromorphy of semi-local zeta functions relative to large finite subsets.

We first show the last claim of the Theorem. For  $\epsilon > 0$ , let  $F_0 \subset\subset G$  as in the proof of Claim 6.2. let  $F', F \supset F_0$  be other finite subgraphs. Let  $F_1 := F \cup F'$ .

$$\frac{\zeta_{F_1}^G(z)}{\zeta_F^G(z)} = \exp \sum_{n \geq 1} \frac{z^n}{n} \#\{x \in \Sigma : \sigma^n(x) = x \text{ and } \{x_0, \dots, x_{n-1}\} \text{ meets } F_1 \text{ but not } F\}.$$

The radius of convergence of the above series is at least  $e^{-h(G \setminus F_0)} \geq e^{-h_\infty(G) - \epsilon}$ . The same applies to  $\zeta_{F_1}^G(z)/\zeta_{F'}^G(z)$ . This proves that  $\zeta_F^G(z)/\zeta_{F'}^G(z)$  is a holomorphic non-zero function over  $|z| < e^{-h_\infty(G) - \epsilon}$ .

We now show that all semi-local zeta functions are meromorphic on  $|z| < e^{-h_\infty(G)}$ , finishing the proof of Theorem 4.

Let  $F \subset\subset G$ . Let  $\epsilon > 0$ . By taking  $H$  such that  $F \subset H \subset\subset G$ ,  $H$  large enough, we can ensure that

$$h(G \setminus H, G \setminus F) \leq h_\infty(G \setminus F) + \epsilon$$

(see the definition in Proposition 4.10). After possibly increasing  $H$ , Claim 6.2 ensures that  $\zeta_{H \setminus F}^{G \setminus F}(z)$  has a meromorphic extension to  $|z| < \exp -h_\infty(G \setminus F) - \epsilon$ . We compute:

$$\begin{aligned} (23) \quad \zeta_H^G(z)/\zeta_F^G(z) &= \exp \sum_{n \geq 1} \frac{z^n}{n} \#\{x \in \Sigma(G) : \sigma^n x = x \text{ and} \\ &\quad \{x_0, \dots, x_{n-1}\} \cap H \neq \emptyset \text{ but } \{x_0, \dots, x_{n-1}\} \cap F = \emptyset\} \\ &= \exp \sum_{n \geq 1} \frac{z^n}{n} \#\{x \in \Sigma(G \setminus F) : \sigma^n x = x \text{ and} \\ &\quad \{x_0, \dots, x_{n-1}\} \cap (H \setminus F) \neq \emptyset\} \\ &= \zeta_{H \setminus F}^{G \setminus F}(z) \end{aligned}$$

By the choice of  $H$ , this function is meromorphic on  $|z| < \exp -h_\infty(G \setminus H) - \epsilon$ . But  $h_\infty(G \setminus H) \leq h_\infty(G)$  (see the remark after Definition 1.9). Thus  $\zeta_F^G(z) =$

$\zeta_H^G(z)/\zeta_{H\setminus F}^G(z)$  is meromorphic on  $|z| < \exp -h_\infty(G\setminus H) - \epsilon$ . Letting  $\epsilon > 0$  decrease to 0, finish the proof of Theorem 4.

## 7. PROOF OF THE CONSEQUENCES

**7.1. Measures of maximum entropy.** Our Structure Theorem implies that the set of maximum measures for a  $*$ -QFT puzzle or for the associated Markov shift have the same cardinality. We apply some results of Gurevič.

First, according to [12], each irreducible subshift of a Markov shift carries at most one maximum measure and this measure, if it exists, is a Markov measure (which implies by [18] that it is a finite extension of a Bernoulli). Hence, a  $*$ -QFT puzzle has at most countably many maximum measures (because it has at most countably many states) and a QFT puzzle has only finitely many irreducible components (because its spectral decomposition contains finitely many irreducible subshifts with maximum entropy).

The existence of a maximum measure for a QFT puzzle follows from the fact that its spectral decomposition must contain an irreducible subshift with entropy equal to that of the puzzle and that this subshift must be SPR, hence positively recurrent which is equivalent to the existence of a maximum measure by the same result of Gurevič. Theorem 2 is proved.

**7.2. Zeta functions.** Recall that for the results involving the counting of the periodic points, we assume, in addition to QFT, determinacy. For simplicity, we assume that the Markov diagram  $\mathcal{D}$  is irreducible and leave the general case to the reader. Let  $\epsilon > 0$ . Theorem 1 gives a large integer  $N$  such that the  $n$ -periodic orbits of  $i_N(X_V)$  and the loops of  $\mathcal{D}$  going through  $\mathcal{D}_N$  can be identified up to an error bounded by  $\exp(h_C(V) + h_{\text{wloc}}(V) + \epsilon)n$ . Hence

$$\zeta^N(z) := \exp \sum_{n \geq 1} \frac{z^n}{n} \#\{x \in i_N(X_V) : F_V^n(x) = x\}$$

is equal to the semi-local zeta function of  $\mathcal{D}$  at  $\mathcal{D}_N$  up to a holomorphic, non-zero factor on the disk  $|z| < e^{-h_C(V) - h_{\text{wloc}}(V) - \epsilon}$  by Claim (3) of Theorem 1. By Theorem 4, this semi-local zeta function can be extended to a meromorphic function on  $|z| < e^{-h_C(V) - h_{\text{wloc}}(V)}$ , proving the main claim.

The singularities of  $\zeta^N(z)$  on  $|z| = e^{-h_{\text{top}}(V)}$  are as claimed by the same statement proved for local zeta function ( $F$  reduced to one vertex) by Gurevic and Savchenko [14].

This concludes the proof of Theorem 3.

**7.3. Equidistribution of periodic points.** We give a sketch of the proof which is essentially that from [8] using the estimates of the analysis of the zeta function above.

There is equidistribution for an irreducible SPR Markov shift according to Gurevic and Savchenko [14]. For the (easy) extension to the general case, it is enough to see (like in [8]) that the number of  $n$ -periodic points living on an irreducible SPR Markov shift  $\Sigma$  with period  $p$  is  $pe^{nh_{\text{top}}(\Sigma)}$  if  $n$  is a multiple of  $p$ , zero otherwise.

To apply it to the puzzle, one has to recall the following facts from the above analysis of the zeta function:

- the projection  $\Sigma(\mathcal{D}) \rightarrow \underline{X}_V$  is continuous;

- there is a one-to-one, period-preserving correspondence between  $i_N$ -projections of periodic points going through a large finite subset  $F$  and a subset of the periodic points of  $X_V$ ;
- the remaining periodic points both on  $i_N(X_V)$  and  $\Sigma(\mathcal{D})$  contributes negligibly to the considered measures by the reasoning in the proof of Theorem 3.

## 8. APPLICATION TO ENTROPY-EXPANDING MAPS

We prove Theorem 8: smooth entropy-expanding maps introduced in [4] define determined puzzles of quasi-finite type, provided that they are endowed with a good partition in the sense of section 1.5. We give some consequences of this in Corollaries 8.2-8.3. The first corollary is a new proof of results in [6] under an additional assumption. The second is new.

**8.1. Puzzle and consequences.** At this point,  $T$  may be just a continuous self-map of a compact metric space  $M$  together with a finite partition  $P$  into subsets  $A$  such that  $\bar{A} = \overline{\text{int}(A)}$  and  $T|_{\bar{A}}$  is one-to-one.  $\mathcal{P}$  is the set of the interiors of the elements of  $P$ .

The puzzle is defined by the refining sequence of "partitions"  $\mathcal{P}_n$  which are, for each  $n \geq 1$ , the set of *almost connected components* of the  $\mathcal{P}$ ,  $n$ -cylinders, i.e., intersections of the form  $A_0 \cap T^{-1}A_1 \cap \dots \cap T^{-n+1}A_{n-1}$ ,  $A_i \in \mathcal{P}_n$ . We assume that each  $\mathcal{P}$  is finite. Their advantage over the usual connected components is the following estimate (to be proved later):

**Proposition 8.1.** *For the puzzle  $V$  defined by almost connected components of the  $P$ -cylinders:*

$$h_C(V) \leq h_{\text{top}}(T, \partial P) + h_{\text{mult}}(T, P)$$

where  $h_{\text{mult}}(T, P) := \limsup_{n \rightarrow \infty} \frac{1}{n} \log \text{mult}(P^n)$  with  $\text{mult}(Q) := \max_{x \in M} \#\{A \in Q : \bar{A} \ni x\}$ .

We shall show that the puzzle defined in this way by an entropy-expanding map with a good partition is close to the original dynamics and also satisfies the assumptions of our theory. Recall the following notions.

The *coding map*  $\gamma_V$  of  $(M, T, (\mathcal{P}_n)_{n \geq 1})$  (or just the coding of  $V$ ) is the partially defined map  $\gamma : M' \rightarrow X_V$  defined by (i)  $M' := \bigcap_{n \geq 1} \bigcup_{A \in \mathcal{P}_n} A$ ; (ii)  $\gamma(x)$  is the unique  $y \in X_V$  such that, for all  $n \geq 1$ ,  $T^n x \in y_n$ . The coding for the usual symbolic dynamics, simply denoted by  $\gamma$ , is obtained in this way by considering the partitions into cylinders of given order:  $\mathcal{P}^1, \mathcal{P}^2, \dots$ .

A finite extension of  $F : X \rightarrow X$  is a skew product over  $F$  with finite fibers, i.e.,  $G : Y \rightarrow Y$  such that  $Y \subset X \times \mathbb{N}$ ,  $\#(Y \cap \{x\} \times \mathbb{N}) < \infty$  for all  $x \in X$ , and  $G(x, n) = (F(x), \Psi(x, n))$  for some  $\Psi : X \times \mathbb{N} \rightarrow \mathbb{N}$ .

A periodic extension of  $F : X \rightarrow X$  is a map of the form  $H : X \times \{0, \dots, p-1\} \rightarrow X \times \{0, \dots, p-1\}$  with  $H(x, j) = H(x, j+1)$  and  $H(x, p-1) = (F(x), 0)$ .

**Theorem 8.** *Let  $T : M \rightarrow M$  be a  $C^\infty$  entropy-expanding map of a compact manifold. Assume that  $\mathcal{P}$  is a good partition and let  $(V, i, f)$  be the puzzle obtained by taking the almost connected components of the  $\mathcal{P}$ ,  $n$ -cylinders,  $n \geq 0$  (see section 2.2). Let  $\gamma_V$  be the coding,*

*Then:*

- (1)  $\gamma_V$  defines an entropy-conjugacy between  $(X_V, F_V)$  and  $(M, T)$ , possibly up to a finite extension: there is a Borel finite extentsion  $G$  of  $F_V$  and an entropy conjugacy of  $G$  and  $T$  which covers  $\gamma_V$ ;
- (2)  $h_C(V) \leq h^{d-1}(T) < h_{\text{top}}(T) = h_{\text{top}}(V)$ ;
- (3)  $V$  is of quasi-finite type with  $h_{\text{wloc}}(V) = 0$ ;
- (4) One can find a determined subpuzzle  $V' \subset V$  such that the two previous properties still hold and only few periodic orbits are destroyed:
- (24) 
$$\forall N \geq 1 \limsup_{n \rightarrow \infty} \frac{1}{n} \log \#\{\xi \in i_N(X_V) : \xi = F_V^n(\xi) \text{ and } \xi \notin i_N(X_{V'})\} \leq h^{d-1}(T).$$

Applying Theorems 2 and 6 to  $V$  yields a new proof of a slightly weaker version of our result [6] about the measures of large entropy of entropy-expanding maps:

**Corollary 8.2.** *Let  $T : M \rightarrow M$  be a  $C^\infty$  entropy-expanding map. Let  $\mathcal{P}$  be a good partition. Then:*

- $T$  has finitely many ergodic, invariant probability measure with maximum entropy.
- the natural extension of such maps  $T$  are classified up to entropy-conjugacy and possibly a period and a finite extension by their topological entropy.

Theorem 3 applied to  $V'$  gives information about periodic points:

**Corollary 8.3.** *In the same setting, let  $\epsilon > 0$ . Perhaps after replacing  $\mathcal{P}$  with a finer good partition, the Artin-Masur zeta function at level  $\mathcal{P}$  of  $T$ :*

$$\zeta_{\mathcal{P}}(z) := \exp \sum_{n \geq 1} \frac{z^n}{n} \#\{\alpha \in \gamma(M') : \sigma^n \alpha = \alpha\}$$

*is holomorphic on the disk  $|z| < e^{-h_{\text{top}}(T)}$  and has a meromorphic extension to the larger disk  $|z| < e^{-h^{d-1}(T)-\epsilon}$ . In particular, there exist integers  $p \geq 1$  and  $m \geq 1$  such that for  $n \rightarrow \infty$  along the multiples of  $p$ :*

$$\#\{\alpha \in \gamma(M') : \sigma^n \alpha = \alpha\} \sim m e^{nh_{\text{top}}(f)}$$

Beyond the new information on periodic points, the point of this new approach is that it separates the purely combinatorial arguments involving the puzzle itself and the ones involving the geometry and smoothness.

PROOF OF COROLLARIES 8.2-8.3: Corollary 8.2 is a trivial consequence of point 1 of Theorem 8 together with Theorems 2 and 6.

Corollary 8.3 follow similarly from points 3 and 4 of Theorem 8 together with Theorem 3 using as the refined finite good partition, the partition defined by the almost connected components of the  $\mathcal{P}, N$ -cylinders where  $N = N(\epsilon)$  is given by Theorem 3.  $\square$

*Remark.* (1) If  $M$  is one or two-dimensional, then a topological argument easily shows that each periodic sequence in the coding  $\gamma(M')$  correspond to a periodic point (e.g., using Brouwer fixed point theorem in connected components of the closure of cylinders). In higher dimension, one must use the non-uniform expansion.

(2) The results of Kaloshin [19] show that upper bounds on the number of periodic points can only hold after some identifications.

In the sequel we prove Theorem 8.



## 8.2. Entropy-conjugacies.

**Lemma 8.4.** *Let  $T : M \rightarrow M$  be an entropy-expanding map with a good partition  $\mathcal{P}$ . Then the puzzle defined by almost connected components of cylinders has the same entropy as  $T$ . More precisely, the coding  $\gamma_V$  defines an entropy-conjugacy between  $T$  and a Borel finite extension of  $F_V$ .*

To prove this, we use a common extension  $X_V \times M$  of the puzzle and of  $T$  defined as:

$$X_V \times M = \overline{\{(v, x) \in X_V \times M : \forall n \geq 0 \ x \in v_n\}}$$

endowed with the map  $F_V \times T$  which is just the restriction of the direct product. Let  $\pi_1$ , resp.  $\pi_2$ , be the projection  $X_V \times M \rightarrow X_V$ , resp.  $X_V \times M \rightarrow M$ .

- We claim that  $F_V \times T$  and  $T$  are entropy-conjugate. Observe that, the partition being good for  $T$ , no point returns infinitely many times to  $\partial P$ . Hence  $\partial P$  has zero measure w.r.t. any  $T$ -invariant probability measure. The same is true for  $\pi_2^{-1}(\partial P)$ . Hence  $(v, x) \mapsto x$  is an isomorphism w.r.t. any invariant probability measure, proving the claim. In particular,  $h_{\text{top}}(F_V \times T) = h_{\text{top}}(T)$  by the variational principle.

- We claim that  $F_V \times T$  and  $F_V$  are entropy-conjugate, perhaps after replacing the latter  $F_V$  by a Borel finite extension. As the extension is continuous and compact, any invariant probability measure of  $F_V$  can be lifted to  $F_V \times T$ . We have to show that, given a large entropy measure of  $F_V$  (1) there are only finitely many ergodic lifts  $\hat{\mu}$ ; (2) for each such  $\hat{\mu}$ ,  $\pi_2 : (X_V \times M, \hat{\mu}) \rightarrow (X_V, \pi_2 \hat{\mu})$  is a finite extension.

We first prove point (2). Let  $\hat{\mu}$  be an arbitrary  $F_V \times T$ -invariant and ergodic probability measure with  $h(F_V \times T, \hat{\mu}) > h^{d-1}(T)$  (this is possible because of the entropy-expansion assumption and the fact that  $h_{\text{top}}(F_V \times T) = h_{\text{top}}(T)$ ). Let  $\mu = (\pi_2)_* \hat{\mu}$  and  $\nu = (\pi_1)_* \hat{\mu}$ .  $\mu$  is a  $T$ -invariant ergodic measure satisfying  $h(T, \mu) = h(F_V \times T, \hat{\mu})$  by the previous paragraph so  $h(T, \mu) > h^{d-1}(T)$ . By [6] this implies that  $\mu$  has only strictly positive Lyapunov exponents, hence, by [7],  $\pi_2 : (X_V \times M, \hat{\mu}) \rightarrow (X_V, \nu)$  is a finite extension. This proves point (2).

We prove point (1) following [7]. Assume by contradiction that there exists infinitely many distinct ergodic lifts  $\hat{\mu}_1, \hat{\mu}_2, \dots$  of some ergodic and invariant probability measure  $\mu$  of  $F_V$ . We can assume that  $\hat{\mu}_n$  converges to some  $\hat{\mu}_*$ . As  $\pi_2$  is continuous,  $\hat{\mu}_*$  is also a lift of  $\mu$  and so are almost all of its ergodic components. They project on  $M$  to ergodic invariant probability measures with positive Lyapunov exponents. As explained in [7], this implies that for each such ergodic component  $\hat{\nu}$ , for  $\hat{\nu}$ -a.e.  $(v, x)$ , there exists a ball  $B$  around  $x$  in the fiber which contains no generic point wrt any measure distinct from  $\hat{\nu}$ . It follows that there are only countably (or finitely) many ergodic components. Thus, there exists an ergodic component of  $\hat{\mu}_*$ , such that the union of these fibered neighborhood has positive  $\hat{\mu}_*$ -measure. Hence it has positive measure for  $\hat{\mu}_n$  for  $n$  large. But this implies that  $\hat{\mu}_n = \hat{\mu}_*$ , a contradiction. Point (1) is proven and the claim follows.

The above two claims prove the lemma and therefore Lemma 8.4.

**8.3. Constraint entropy.** Before proving Proposition 8.1 which will imply claim 2 of Theorem 8, we give a geometric necessary condition for the irreducibility of puzzle pieces.

**Lemma 8.5.** *Let  $(V, i, f)$  be a puzzle generated by the almost connected components of the cylinders of a partition  $\mathcal{P}$ .*

*Let  $v \in V$  and let  $A$  be the unique the element of  $\mathcal{P}$  containing  $v$ ,*

$$\overline{f(v)} \cap \partial T(A) = \emptyset \implies v \text{ is } f\text{-reducible.}$$

PROOF: Assume  $\overline{f(v)} \cap \partial T(A) = \emptyset$ .  $v$  is an almost connected component of  $A \cap T^{-1}(f(v)) = (T|_{\bar{A}})^{-1}(f(v))$ . By the assumption, this last set is uniformly homeomorphic to  $f(v)$ , hence is almost connected. Therefore it is equal to  $v$ .

This shows that  $v$  is uniquely determined by  $f(v)$  and  $A = i_1(v)$  (*a fortiori*  $i(v)$ ), verifying condition (2) of reducibility.

Consider now (\*)  $f : \mathcal{T}_i(v) \rightarrow \mathcal{T}_i(f(v))$ . Observe that for any  $w \in \mathcal{T}_i(f(v))$ ,  $w \subset f(v)$ . Hence,  $\overline{w} \cap \partial T(A) = \emptyset$ . The reasoning for the uniqueness of  $v$  shows that the map (\*) is one-to-one:  $f(u) = f(u')$  implies that  $T(u)$  and  $T(u')$  are both almost connected subsets of  $f(u) = f(u')$ , so they must be equal.

For  $w \in \mathcal{T}_i(f(v))$ ,  $u = (T|_A)^{-1}(w) \in \mathcal{T}_i(v)$  satisfies  $w = f(u)$ . Hence the map (\*) is onto and therefore an isomorphism, proving condition (1) of reducibility.  $\square$

PROOF OF PROPOSITION 8.1: Let  $r > 0$  and  $\epsilon > 0$ . We are going to bound by  $e^{(h_{\text{top}}(T, \partial \mathcal{P}) + h_{\text{mult}}(T, \mathcal{P}) + 2\epsilon)n}$  the cardinality of  $\Sigma_n$  an arbitrary  $(r, n)$ -separated subset of  $\mathcal{C}_n$ , the set of irreducible pieces of order  $n$ . Recall that there exists some  $L = L(r)$ , for all  $n \geq L$ ,  $x, x' \in V_n$  are  $(r, n)$ -separated if there exists some  $0 \leq k < n - L$  such that  $(f^k x)_L \neq (f^k x')_L$ .

Let  $\rho > 0$  be smaller than the distance between any two almost connected component of any  $L$ -cylinder (there are only finitely many of them,  $L$  being fixed, and the distance between any two of them is positive as we are considering **almost** connected components). As  $\mathcal{P}$  is a good partition,  $\text{mult}(\mathcal{P}^n) \leq (\#\mathcal{P})^{d+1}$  for all  $n \geq 1$ . Hence, for all integers  $n$  large enough,  $\text{mult}(\mathcal{P}^n) \leq e^{\epsilon N}$ . As  $n$  is large,  $r(\rho/2, n, \partial \mathcal{P}) \leq e^{(h_{\text{top}}(T, \partial \mathcal{P}) + \epsilon)n}$  for all  $n \geq N$ .

Let  $S_n$  be a minimal  $(\rho/2, n)$ -spanning subset of  $\partial P$ . To every  $v \in \Sigma_n$ , associate a point  $x = x(v) \in S_n$  such that  $d(T^k v, T^k x) < \rho/2$  for all  $0 \leq k < n$  ( $T^k v$  is a subset of  $M$ ). This is possible since  $\bar{v} \cap \partial P \neq \emptyset$  by Lemma 8.5.

The map  $x : \Sigma_n \rightarrow S_n$  is at most  $C e^{(h_{\text{mult}}(T, \mathcal{P}) + \epsilon)n}$ -to-1. Indeed, assume that there exists  $x \in S_n$  with more than  $e^{(h_{\text{mult}}(T, \mathcal{P}) + \epsilon)n}$  pre-images. By dividing the pre-images into a constant number  $C$  of subsets, we can assume that  $(f^k v')_L = (f^k v)_L$  for  $n - L \leq k < n$ . As  $e^{(h_{\text{mult}}(T, \mathcal{P}) + \epsilon)n} > \text{mult}(\mathcal{P}^n)$ , two of the preimages, say  $v$  and  $v'$ , must correspond to the same  $n, \mathcal{P}$ -cylinder. But  $d(T^k v, T^k v') \leq d(T^k v, T^k x) + d(T^k x, T^k v') < \rho$ , which is not more than the distance between any two distinct almost connected components of the relevant  $L$ -cylinder. Hence  $(f^k v')_L = (f^k v)_L$  for all  $0 \leq k < n - L$ , a contradiction. This implies  $\#\Sigma_n \leq C e^{(h_{\text{mult}}(T, \mathcal{P}) + \epsilon)n} \#S_n$ :

$$h_{\mathcal{C}}(F_V) \leq h_{\text{top}}(T, \partial \mathcal{P}) + h_{\text{mult}}(T, \mathcal{P}) + 2\epsilon,$$

with arbitrary  $\epsilon > 0$ , proving the claim.  $\square$

**8.4. Determination.** We turn to the fourth claim of Theorem 8. The delicate point here is that it is possible (though exceptional) that  $u \succeq_f v$  in the absence of the geometric property of Lemma 8.5.

A puzzle piece  $v \in V$  is *trivial* if there exists  $k \geq 1$  such that for every  $w \in \mathcal{T}_i(v)$ ,

$$(25) \quad w \cap T^k(\partial \mathcal{P}) \neq \emptyset.$$

The *trivial subset* of  $V$  is the smallest subset  $V^*$  of the puzzle such that:

- $V^*$  contains all trivial pieces;
- if  $f(v) \in V^*$  then  $v \in V^*$ .

The *non trivial puzzle* is  $V \setminus V^*$  with the maps  $i$  and  $f$  obtained by restriction.

**Lemma 8.6.** *Let  $(V, i, f)$  be the puzzle defined by a dynamical system  $T : M \rightarrow M$  as in Proposition 8.1.*

*The non trivial puzzle  $V' := V \setminus V^0$  is again a puzzle and  $V'$  is determined.*

*Assume additionally that  $h_C(V) < h_{\text{top}}(V)$ . Then the obvious injection  $i : X_{V'} \rightarrow X_V$  is an entropy-conjugacy and the approximate periodic points of the two systems satisfy the estimate (24) of Theorem 8:*

$$\forall N \geq 1 \limsup_{n \rightarrow \infty} \frac{1}{n} \log \#\{\xi \in i_N(X_V) \setminus i_N(X_{V'}) : \sigma^n \xi = \xi\} \leq h_C(V).$$

PROOF: Note the following easy facts: (i)  $V^0 = \bigcup_{k \geq 0} f^{-k}V^*$  if  $V^*$  denotes the trivial pieces of  $V$ ; (ii) if  $\mathcal{I}_i(v) \subset \mathcal{I}_i(v')$  then  $v' \in V^* \implies v \in V^*$ .

(i) immediately gives that:  $v \notin V^0 \implies f(v) \notin V^0$ . Now, if  $i(v) \in V^0$ ,  $f^k(i(v)) = i(f^k(v)) \in V^*$  for some  $k \geq 0$  and therefore  $f^k(v) \in V^*$  by (ii). Hence  $v \notin V^0 \implies i(v) \notin V^0$ . Thus,  $V'$  is a puzzle.

For the determinacy, consider  $v, v', w \in V'$  such that  $i_1(v) = i_1(v') =: A \in \mathcal{P}$  and  $v, v' \succeq_f w$ . Assume by contradiction that  $v \neq v'$ .  $T|_A$  is a homeomorphism hence  $v, v'$  are almost connected components of  $(T|_A)^{-1}(TA \cap w)$ .  $v, v' \succeq_f w$  implies that:

$$\{f(u) : u \in \mathcal{I}_i(v)\} = \{f(u') : u' \in \mathcal{I}_i(v')\} = \mathcal{I}_i(w)$$

Hence, every  $t \in \mathcal{I}_i(w)$  meets both almost connected sets  $T(u) \subset T(v)$  and  $T(u') \subset T(v')$  with  $u \in \mathcal{I}_i(v)$ ,  $u' \in \mathcal{I}_i(v')$ . Therefore  $t \cap \partial T(v) \setminus \partial w$ , so that  $t \cap T\partial A \neq \emptyset$ . Thus  $w$  is trivial, contrarily to assumptions. Thus  $V'$  is determined.

We now let  $\mu$  be an ergodic  $F_V$ -invariant probability measure such that, for some  $v \in V^0$ ,  $\mu([v]_V) > 0$ . This implies that  $\mu([f^k(v)]_V) > 0$  for some  $k < |v|$  such that  $f^k v$  is trivial. We can assume  $k = 0$ . It is now immediate that

$$h(F_V, \mu) \leq h_{\text{top}}(F_V, [v]_V) \leq h_C(V) < h_{\text{top}}(V).$$

proving the entropy-conjugacy.

Consider now the periodic sequences  $\xi \in i_N(X_V) \setminus i_N(X_{V'}) \subset i_N(X_V \setminus X_{V'})$ . Hence  $\xi = i_N(x)$  with  $f^n(x_{n+m}) \in V^0$  for some  $n, m \geq 0$ . As above, we can assume that in fact  $f^n(x_{n+m}) \in V^*$ . As we are interested only in periodic orbits and an exponential estimate, we can assume that  $n = 0$ . But  $x_m \in V^*$  implies that for all  $k \geq m$ ,  $x_k \in V^*$ , hence  $x_k \cap T\partial P \neq \emptyset$ . Let

$$S := \{x \in X_V : \forall k \geq 1 x_k \cap T\partial P \neq \emptyset\}$$

It is easily seen as above that  $h_{\text{top}}(F_V, S) \leq h_C(V)$ . This implies the claim of the Lemma for all  $N \geq 1$ .  $\square$

**8.5. W-local Entropy.** We prove the third point of Theorem 8:

**Lemma 8.7.** *If  $V$  is a  $*$ -QFT puzzle which is determined then, for all invariant and ergodic probability measure  $\mu$  on  $X_V$  with  $h(F_V, \mu) > h_C(V)$ ,*

$$h(F_V, \mu) = h(F_V, \mu, \epsilon_*)$$

*So in particular,  $h_{\text{wloc}}(V) = 0$ .*

PROOF: Any ergodic invariant probability measure with entropy  $> h_C(V)$  can be lifted to an isomorphic  $\hat{\mu}$  on  $\Sigma(\mathcal{D})$  by Theorem 1.  $h(\sigma^{-1}, \hat{\mu}) = h(\sigma, \hat{\mu}) = h(F_V, \mu)$  can be bounded by the growth rate of the number paths on  $\mathcal{D}$  ending at any fixed vertex  $v_* \in \mathcal{D}$  with  $\hat{\mu}([v]_{\Sigma(\mathcal{D})}) > 0$ . But those paths are uniquely determined by their  $i_1$ -projection as  $V$  is determined (Lemma 5.1). Thus,  $h(F_V, \mu) = h(\sigma, i_1(\mu)) = h(F_V, \mu, 1/2)$ .  $\square$

**Corollary 8.8.** *Let  $V$  be a  $*$ -QFT puzzle with a subpuzzle  $V'$  which is determined. Assume that  $F_V$  and  $F_{V'}$  are entropy-conjugate wrt ergodic invariant probability measures with entropy  $> h_C(V)$ . Then  $h_{\text{wloc}}(V) = 0$ .*

PROOF: Let  $\mu$  be an ergodic invariant probability measure of  $X_V$  with  $h(F_V, \mu) > h_C(V)$ . Hence, it can be identified to an invariant measure  $\mu'$  of  $F_{V'}$ . Therefore  $h(F_{V'}, \mu') = h(\sigma, i_N(\mu'))$  for some integer  $N \geq 1$ . But  $V' \subset V$  hence one can define almost everywhere  $i_N : X_V \rightarrow i_N(X_{V'})$  and check that  $i_N(\mu)$  and  $i_N(\mu')$  are isomorphic so that  $h(F_V, \mu) = h(\sigma, i_N(\mu))$ , proving the claim.  $\square$

#### APPENDIX A. VARYING RADIUS OF MEROMORPHY

**Definition A.1.** *Denote by  $\mathbf{M}(f)$  the radius of meromorphy of a formal power series  $f$ . It is zero if the radius of convergence of  $f$ ,  $\rho(f)$ , is zero. Otherwise it is the supremum of the radiuses  $r$  of the disks  $D(r)$  centered at zero for which there exists a rational function  $F(z)$  such that  $f(z)/F(z)$  can be extended to a holomorphic and non-zero function on  $D(r)$ .*

**Fact A.2.** *There exists a countable oriented SPR graph  $G \ni a, b$  such that  $\mathbf{M}(\zeta_a^G) \neq \mathbf{M}(\zeta_b^G)$ .*

We found this example after an illuminating discussion with O. Sarig.

Before giving our construction, we recall some basic tools. The main tool here is the notion of a loop graph (or petal graph in the terminology of B. Gurevič). These graphs have a distinguished vertex and an arbitrary number of simple loops<sup>5</sup> of each length based at the distinguished vertex, but distinct first return loops are disjoint except for the distinguished vertex. Such graphs are completely described by their *first return series*  $f(z) := \sum_{n \geq 1} f_n z^n$  where  $f_n$  is the number of simple loops of length  $n$  (based at the distinguished vertex). It is well-known that the local zeta function at the distinguished vertex is

$$\zeta_*^G(z) = \frac{1}{1 - f(z)} = \sum_{n \geq 1} \ell_n z^n$$

where  $\ell_n$  is the number of loops of length  $n$  based at the distinguished vertex<sup>6</sup>.

We now give the construction. We consider two disjoint loop graphs defined by first return series  $a(z) := \sum_{n \geq 1} a_n z^n$  and  $b(z) := \sum_{n \geq 1} b_n z^n$ . We call their respective distinguished vertices  $a$  and  $b$ .

We define a new graph  $G$  by taking the disjoint union of:

- the two preceding loop graphs;

<sup>5</sup>That is, sequences  $v_0 \xrightarrow{e_1} v_1 \rightarrow \dots \xrightarrow{e_n} v_n$  where the vertices  $v_i$ 's and edges  $e_i$ 's are distinct except for  $v_0 = v_n$  which is the distinguished vertex. Such sequences are called first return loops of length  $n$ .

<sup>6</sup>These loops may go several times through the base.

- a set of disjoint paths from  $a$  to  $b$  described by a series  $s(z) := \sum_{n \geq 1} s_n z^n$  (there are  $s_n$  simple paths of length  $n$  from  $a$  to  $b$  and these are disjoint);
- set of simple paths from  $b$  to  $a$  described by a series  $t(z) := \sum_{n \geq 1} t_n z^n$ .

**Claim A.3.** *The first return series of  $G$  at  $a$  is:*

$$\hat{a}(z) = a(z) + \frac{s(z)t(z)}{1 - b(z)}$$

Indeed, a first return loop at  $a$  in  $G$  is:

- a first return loop in the loop graph  $a$ ;
- a transition from  $a$  to  $b$ , followed by a (non necessarily first return) loop at  $b$ , a transition from  $b$  to  $a$ .

Fix  $b(z) = 2z^2$  (so the associated Markov shift is the set of all infinite concatenations of the two words of length 2, say  $b0$  and  $b1$ ).

Let  $\tau(z) := \sum_{n \geq 1} \tau_n z^n = s(z)t(z)$ . We can arrange it so:

- $\tau_0 = \tau_1 = 0$ ,  $\tau_n = 0$  or  $1$ ;
- $|z| = 1$  is the natural boundary of  $\tau$  (by the Polya-Carlson theorem, this is equivalent to  $\tau$  not being rational).

It follows that  $q(z) := \tau(z)/(1 - b(z))$  satisfies:

- (1)  $q_0 = 0$ ,  $0 \leq q_n \leq 2^{n+1} \leq 5^n$
- (2)  $|z| = 1$  is the natural boundary of  $q$ .

Now, set  $a_0 = 0$  and, for  $n \geq 1$ :  $a_n := 5^n - q_n \geq 0$ . We have:  $\hat{a}_n = a_n + q_n = 5^n$  for  $n \geq 1$ ,  $\hat{a}_0 = 0$ . Hence  $\hat{a}(z) = z/(1 - 5z)$  and

$$\zeta_a^G(z) = \frac{1}{1 - \hat{a}(z)} = \frac{1 - 5z}{1 - 6z}$$

is a rational function. In particular,  $\mathbf{M}(\zeta_a^G) = \infty$ . On the other hand,

$$\hat{b}(z) = b(z) + \frac{\tau(z)}{1 - a(z)} = 2z^2 + \frac{(1 - 2z^2)q(z)}{1 - \frac{z}{1-5z} + q(z)} = 2z^2 + \frac{(1 - 2z^2)(1 - 5z)}{1 + (1 - 6z)/q(z)}$$

Therefore  $\zeta_b^G(z) = 1/(1 - \hat{b}(z))$  has meromorphy radius:  $\mathbf{M}(\zeta_b^G) = \mathbf{M}(\hat{b}) = \mathbf{M}(q) = 1$ . Thus,

$$\mathbf{M}(\zeta_b^G) < \mathbf{M}(\zeta_a^G)$$

as claimed.

Observe that  $h(G) = \log 6$  and  $h_\infty(G) = \log 5$ . Hence  $h_\infty(G) < h(G)$  and  $G$  is SPR as claimed, finishing the construction.

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