

ON ENTROPY AND GENERATORS OF MEASURE-PRESERVING TRANSFORMATIONS

BY
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Abstract. Let T be an ergodic measure-preserving transformation of a Lebesgue measure space with entropy $h(T)$. We prove that T has a generator of size k where $e^{h(T)} \leq k \leq e^{h(T)} + 1$.

1. Introduction. In this paper we are concerned with ergodic invertible measure-preserving transformations of a Lebesgue measure space $(E, \mathfrak{B}, p)$. By a partition $\{A_n : n \in \theta\}$ of E we shall mean a finite or countably infinite collection of disjoint sets $A_n \in \mathfrak{B}$ of positive measure such that

$$E = \bigcup_{n \in \theta} A_n.$$

We call a partition $\{A_n : n \in \theta\}$ a generator of an i.m.p.t. T of $(E, \mathfrak{B}, p)$ if $\mathfrak{B}$ is generated by

$$\bigcup_{i=-\infty}^{\infty} \{T^i A_n : n \in \theta\}.$$

For the theory of entropy and generators of i.m.p.t. we refer to [1], [4], [5] and [6]. It was proved by V. A. Rohlin that every aperiodic i.m.p.t. with finite entropy has a generator with finite entropy [6, 10.7]. We shall prove in §2 that every ergodic i.m.p.t. with finite entropy has a finite generator, thereby solving a problem that was posed by V. A. Rohlin [6, p. 30].

Throughout most of this paper we shall be given a finite or countably infinite state space Ω . For finite Ω we shall prove in §3 an approximation theorem for probability measures on $\Omega^{\mathbb{Z}}$ that are invariant under the shift S ,

$$(Sx)_i = x_{i+1}, \quad i \in \mathbb{Z}, \quad x = (x_i)_{i=-\infty}^{\infty} \in \Omega^{\mathbb{Z}}.$$

This theorem will enable us to derive in §4 from the work of A. H. Zaslavskii [7] a formula for the minimal number of elements that a generator of an ergodic i.m.p.t. can contain. Denote this number by $\Delta(T)$. If the entropy $h(T)$ of T is infinite then $\Delta(T)$ is also infinite, if $h(T) < \infty$, then $\Delta(T) \geq e^{h(T)}$. Our result is

$$\Delta(T) \leq e^{h(T)} + 1.$$

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This answers for the ergodic case another question raised by Rohlin [6, p. 30]. In particular it follows that every ergodic i.m.p.t. with entropy zero has a generator with two elements. This was known before in the case of the quasi-discrete spectrum [3, p. 187].

2. The existence of finite generators.

(2.1) THEOREM. *Every ergodic i.m.p.t. with finite entropy has a finite generator.*

Proof. 1. Let $\{A_n : n \in N\}$ be a partition of $(E, \mathfrak{B}, p)$ with finite entropy. Then there exists a mapping $n \rightarrow K_n \in N$ ($n \in N$) and a 1-1 mapping

$$\varphi: N \rightarrow \bigcup_{k=1}^{\infty} \{1, 2, 3\}^k$$

where $\varphi(n) \in \{1, 2, 3\}^{K_n}$, $n \in N$, such that

$$(1) \quad \sum_{n=1}^{\infty} K_n p(A_n) < \infty.$$

For a proof of this let $p(A_n) \geq p(A_{n+1})$, $n \in N$, and let $l(n)$, $n \in N$, be nonnegative integers such that

$$(2) \quad -\log p(A_n) - 1 < l(n) \leq -\log p(A_n), \quad n \in N.$$

Let further

$$n_1 = 1, \quad n_m = \min \{n > n_{m-1} : l(n) > l(n_{m-1})\}, \quad m > 1.$$

Then

$$\sum_{m=1}^{\infty} (n_{m+1} - n_m) 3^{-l(n_m)} = \sum_{n=1}^{\infty} 3^{-l(n)},$$

and we see from (2) that

$$\sum_{m=1}^{\infty} (n_{m+1} - n_m) 3^{-l(n_m)} \leq e.$$

Consequently, for some $m_0 \in N$,

$$(3) \quad n_{m+1} - n_m < 3^{l(n_m)}, \quad m \geq m_0.$$

We set $K_n = l(n)$, $n \geq n_{m_0}$. By (3) it is possible to assign to every $n \geq n_{m_0}$ an element $\varphi(n)$ of $\{1, 2, 3\}^{K_n}$ such that $n \rightarrow \varphi(n)$, $n \geq n_{m_0}$, is 1-1. The inequality (3) also shows that it is possible to define the $\varphi(n) \in \bigcup_{k=1}^{\infty} \{1, 2, 3\}^k$, $1 \leq n < n_{m_0}$, in such a way that

$$\varphi: N \rightarrow \bigcup_{k=1}^{\infty} \{1, 2, 3\}^k$$

is 1-1. In order to show that (1) holds it suffices to show that

$$\sum_{n=n_{m_0}}^{\infty} K_n p(A_n) < \infty,$$

and this follows from the finiteness of the entropy of $\{A_n : n \in N\}$ and from (2):

$$\sum_{n=n_{m_0}}^{\infty} K_n p(A_n) \leq \sum_{n=1}^{\infty} l(n) p(A_n) \leq \sum_{n=1}^{\infty} -p(A_n) \log p(A_n) < \infty.$$

2. Let Ω be a finite set containing more than two elements. Let $\omega \in \Omega$, $C \in N$, and let

$$X = \left\{ x = ((x_{i,j})_{j=1}^{D_i})_{i=-\infty}^{\infty} \in \left(\bigcup_{k=2}^{\infty} \Omega^k \right)^{\mathbb{Z}} : \right. \\ \left. x_{i,j} \neq \omega, 1 \leq j < D_i, x_{i,D_i} = \omega, -\infty < i < \infty \right\},$$

and

$$X_C = \bigcap_{k=-\infty}^{\infty} \bigcup_{l=1}^{\infty} \left\{ x = ((x_{i,j})_{j=1}^{D_i})_{i=-\infty}^{\infty} \in X : \sum_{m=k}^{k+l} (D_m - C) \leq 0 \right\}.$$

We are going to construct a 1-1 Borel mapping $U: X_C \rightarrow (\Omega^C)^{\mathbb{Z}}$ that commutes with the shifts.

Let $x = ((x_{i,j})_{j=1}^{D_i})_{i=-\infty}^{\infty} \in X_C$ and let $\Gamma = \{i \in \mathbb{Z} : D_i > C\}$. We define for $i \in \Gamma$, $C < j \leq D_i$,

$$(4) \quad I(i, j) = \min \left\{ l > i : j - C + \sum_{i < m \leq l} (D_m - C) \leq 0 \right\},$$

$$(5) \quad J(i, j) = j + \sum_{i < m \leq I(i, j)} (D_m - C).$$

It follows that

$$D_{I(i, j)} < J(i, j) \leq C, \quad i \in \Gamma, \quad C < j < D_i.$$

The mapping

$$(i, j) \rightarrow (I(i, j), J(i, j)) \quad (i \in \Gamma, C < j \leq D_i)$$

is 1-1. Indeed, had we $i, i' \in \Gamma$, $C < j \leq D_i$, $C < j' \leq D_{i'}$,

$$(I(i, j), J(i, j)) = (I(i', j'), J(i', j')),$$

and say $i < i'$, then we could infer from (5) that

$$j + \sum_{i < m \leq I(i, j)} D_m = J(i, j) + (I(i, j) - i)C, \\ \sum_{i' \leq m \leq I(i, j)} D_m \geq J(i, j) + (I(i, j) - i')C,$$

and therefore that

$$j + \sum_{i < m < i'} D_m \leq (i' - i)C,$$

in contradiction to $j > C$ or to (4). We define now

$$Ux = ((y_{i,j})_{j=1}^C)_{i=-\infty}^{\infty} \in (\Omega^C)^{\mathbb{Z}}$$

by setting

$$y_{i,j} = x_{i,j}, \quad \text{if } i \in \mathbf{Z}, \quad 1 \leq j \leq \min(C, D_i),$$

$$y_{I(i,j), J(i,j)} = x_{i,j}, \quad \text{if } i \in \Gamma, \quad C < j \leq D_i,$$

and by setting $y_{i,j} = \alpha$, $\alpha \in \Omega$, $\alpha \neq \omega$, elsewhere. U is Borel and it commutes with the shifts. We prove now that it is 1-1 by showing that the D_i , $i \in \Gamma$, can be computed from Ux .

Denote

$$I_\omega(i) = I(i, D_i), \quad J_\omega(i) = J(i, D_i), \quad i \in \Gamma,$$

and

$$N_\omega(i) = \sum_{j=1}^C \delta_{\omega, y_{i,j}}, \quad i \in \mathbf{Z}.$$

We have for $i, i' \in \Gamma$

$$(6) \quad i < i' < I_\omega(i) \Rightarrow I_\omega(i') \leq I_\omega(i),$$

$$(7) \quad i < I_\omega(i') < I_\omega(i) \Rightarrow i < i',$$

$$(8) \quad i < i', \quad I_\omega(i) = I_\omega(i') \Rightarrow J_\omega(i) > J_\omega(i').$$

From these relations and since $i \rightarrow (I_\omega(i), J_\omega(i))$ ($i \in \Gamma$) is 1-1 we have

$$\begin{aligned} & \sum_{i < m < I_\omega(i)} N_\omega(m) + \sum_{j=1}^{J_\omega(i)} \delta_{\omega, y_{I_\omega(i),j}} \\ (9) \quad &= |\{i' \in \mathbf{Z} - \Gamma : i < i' \leq I_\omega(i)\}| + |\{i' \in \Gamma : i < I_\omega(i') < I_\omega(i)\}| \\ &+ |\{i' \in \Gamma : I_\omega(i') = I_\omega(i), J_\omega(i') < J_\omega(i)\}| + 1 \\ &= |\{i' \in \mathbf{Z} - \Gamma : i < i' \leq I_\omega(i)\}| + |\{i' \in \Gamma : i < i' < I_\omega(i)\}| + 1 \\ &= I_\omega(i) - i + 1, \quad i \in \Gamma. \end{aligned}$$

And we have from (7)

$$\begin{aligned} & \sum_{i < m \leq L} N_\omega(m) = |\{i' \in \mathbf{Z} - \Gamma : i < i' \leq L\}| + |\{i' \in \Gamma : i < I_\omega(i') \leq L\}| \\ (10) \quad &= |\{i' \in \mathbf{Z} - \Gamma : i < i' \leq L\}| + |\{i' \in \Gamma : i < i' < L\}| \\ &\leq L - i, \quad i \in \Gamma, \quad i < L < I_\omega(i). \end{aligned}$$

Now we see from (9) and (10) that

$$(11) \quad I_\omega(i) = \min \left\{ L > i : \sum_{i < m \leq L} N_\omega(m) > L - i \right\}, \quad i \in \Gamma$$

and that

$$\begin{aligned} (12) \quad J_\omega(i) = \min \left\{ 1 < l \leq C : \sum_{i < m < I_\omega(i)} N_\omega(m) \right. \\ \left. + \sum_{j=1}^l \delta_{\omega, y_{I_\omega(i),j}} = I_\omega(i) - i + 1 \right\}, \quad i \in \Gamma. \end{aligned}$$

Next we observe that

$$(13) \quad D_i = J_\omega(i) + (I_\omega(i) - i)C - \sum_{i < m \leq I_\omega(i)} D_m, \quad i \in \Gamma.$$

We know from (6) that

$$(14) \quad i < i' < I_\omega(i) \Rightarrow I_\omega(i') - i' < I_\omega(i) - i, \quad i, i' \in \Gamma.$$

It follows that if $i_0 \in \Gamma$ is such that

$$I_\omega(i_0) - i_0 = \min \{I_\omega(i) - i : i \in \Gamma\}$$

then $i_0 < i \leq I_\omega(i_0) \Rightarrow i \in Z - \Gamma$ and we see from (13) that D_{i_0} can be computed from the $y_{i,j}$, $1 \leq j \leq C$, $i \in Z$. Finally (14) implies also that (13) can be used as a recursion formula to compute all the D_i , $i \in \Gamma$, from Ux .

3. By Rohlin's result [6, 10.7] every ergodic i.m.p.t. is isomorphic to the shift on N^Z together with an invariant probability measure μ such that the partition

$$\{(n_i)_{i=-\infty}^\infty \in N^Z : n_0 = m\}, \quad m \in N,$$

has finite entropy. By part 1 of the proof there is a $C \in N$ and a 1-1 mapping

$$n \rightarrow (x_{n,1}, \dots, x_{n,K_n}) \in \bigcup_{k=1}^\infty \{1, 2, 3\}^k \quad (n \in N)$$

such that

$$(15) \quad \sum_{m=1}^\infty K_m \mu(\{(n_i)_{i=-\infty}^\infty \in N^Z : n_0 = m\}) < C - 1.$$

We use this mapping to build a 1-1 mapping

$$V : (n_i)_{i=-\infty}^\infty \rightarrow ((x_{n_i,1}, \dots, x_{n_i,K_{n_i}}, \omega))_{i=-\infty}^\infty \in X \quad ((n_i)_{i=-\infty}^\infty \in N^Z)$$

that commutes with the shifts, where we can set $\Omega = \{1, 2, 3, \omega\}$. The individual ergodic theorem and (15) yield

$$\lim_{L \rightarrow \infty} \frac{1}{L} \sum_{i=1}^L (K_{n_i} + 1 - C) < 0, \quad \text{for } \mu\text{-a.a. } (n_i)_{i=-\infty}^\infty \in N^Z.$$

Hence $\mu(V^{-1}X_C) = 1$.

By part 2 of the proof there is a 1-1 Borel mapping

$$U : X_C \rightarrow \Omega^Z$$

that commutes with the shifts. If we set for a Borel set $F \subset \Omega^Z$,

$$\nu(F) = \mu(V^{-1}U^{-1}F),$$

then we find that (N^Z, μ, S) is isomorphic to (Ω^Z, ν, S) . (If a finite Borel measure on a polish space is transported via a 1-1 Borel mapping to another polish space then the Borel mapping becomes an isomorphism between the measure space

given by μ and the measure space that is given by the transported measure. This can be seen from the fact that every analytic subset of a polish space is measurable with respect to every finite Borel measure (see e.g. [2, §6, n°9]). Q.E.D.

3. An approximation theorem for shift-invariant measures. Let Ω be a state space containing a finite number n of elements, $n \geq 2$. We define for a probability measure μ on Ω^I , $I \in N$, such that $\mu(a) > 0$ for all $a \in \Omega^I$

$$\tilde{h}(\mu) = - \sum_{a=(a_i)_{i=1}^I \in \Omega^I} \mu(a) \log \frac{\mu(a)}{\sum_{\alpha \in \Omega} \mu((a_1, \dots, a_{I-1}, \alpha))}.$$

We denote by $\mathfrak{M}_I$, $I \in N$, the set of all probability measures μ on Ω^I such that $\mu(a) > 0$, $a \in \Omega^I$, and

$$\mu(\{b \in \Omega^I : a = (b_i)_{i=1}^I\}) = \mu(\{b \in \Omega^I : a = (b_{i+m})_{i=1}^I\}), \\ 1 \leq m \leq I-I, \quad a \in \Omega^I, \quad 1 \leq I < I.$$

Further we set

$$Z_a = \{x \in \Omega^{\mathbb{Z}} : a = (x_i)_{i=1}^I\}, \quad a \in \Omega^I, \quad I \in N.$$

For $\mu \in \mathfrak{M}_I$, $I \in N$, we define a shift-invariant probability measure $\hat{\mu}$ on $\Omega^{\mathbb{Z}}$ by

$$\hat{\mu}(Z_a) = \mu(a), \quad a \in \Omega^I, \\ \hat{\mu}(Z_{(\alpha_j)_{j=1}^J}) = \frac{\hat{\mu}(Z_{(\alpha_j)_{j=2}^J}) \hat{\mu}(Z_{(\alpha_j)_{j=1}^{J-1}})}{\hat{\mu}(Z_{(\alpha_j)_{j=1}^{J-1}})}, \quad (\alpha_j)_{j=1}^J \in \Omega^I, \quad J > I.$$

We note that (see [6, 5.10]) $h(\hat{\mu}) = \tilde{h}(\mu)$, $\mu \in \mathfrak{M}_I$, $I \in N$, and that the $\hat{\mu}$ are ergodic. Indeed, the systems $(\hat{\mu}, S^I)$, $\mu \in \mathfrak{M}_I$, arise from indecomposable Markov chains. For probability measures μ, ν on Ω^I , $I \in N$, we use the metric

$$|\mu, \nu| = \max_{a \in \Omega^I} |\mu(a) - \nu(a)|.$$

Let $I, N \in N$, $I < N$. We define for $x \in \Omega^{N+I-1}$ a probability measure $\lambda_x^{(I)}$ on Ω^I by

$$\lambda_x^{(I)}(a) = N^{-1} \sum_{j=1}^N \delta_{a, (x_{j+I-1})_{i=1}^I}, \quad a \in \Omega^I.$$

We set also

$$A(I, \mu, \delta, N) = \{x \in \Omega^{N+I-1} : |\lambda_x^{(I)}, \mu| < \delta\}, \quad \mu \in \mathfrak{M}_I, \quad \delta > 0.$$

(3.1) LEMMA. Let $\mu \in \mathfrak{M}_I$, $I \in N$ and let $\epsilon, \delta > 0$. Then there is an $L > I$ such that

$$|A(I, \mu, \delta, N)| > \exp [(\tilde{h}(\mu) - \epsilon)N], \quad N \geq L.$$

Proof. The mean ergodic theorem and the Shannon-McMillan theorem [1, p. 129] show that there is an $L \in N$ such that for all $N \geq L$

$$\hat{\mu}(\{x \in \Omega^{\mathbb{Z}} : |\lambda_{(x_i)_{i=1}^{N+I-1}}^{(I)}, \mu| < \delta\} \\ \cap \{x \in \Omega^{\mathbb{Z}} : |N^{-1} \log \hat{\mu}(Z_{(x_i)_{i=1}^{N+I-1}}) + \tilde{h}(\mu)| < \epsilon\}) > e^{-\epsilon}.$$

We infer from this that

$$|A(I, \mu, \delta, N)| > \exp [(\tilde{h}(\mu) - \varepsilon)N - \varepsilon], \quad N \geq L. \quad \text{Q.E.D.}$$

We say that an $a \in \Omega^l$, $l \in N$, is a coding sequence if

$$(a_i)_{i=1}^m \neq (a_{i-m+i})_{i=1}^m, \quad 1 \leq m < l.$$

We say that an $a \in \Omega^l$ is an α -coding sequence of length l if $a_i = \alpha$, $1 \leq i < l$ and $a_l = \beta \neq \alpha$. We set for $I, N \in N$, $I < N$, $\mu \in \mathfrak{M}_I$ and $\delta > 0$,

$$B_a(I, \mu, \delta, N) = \{x \in A(I, \mu, \delta, N) : (x_{m+1})_{i=1}^l \neq a, 0 \leq m \leq N - I + 1 - l\}.$$

(3.2) LEMMA. Let $\mu \in \mathfrak{M}_I$, $I \in N$, and let $\delta, \varepsilon > 0$. Then there exists a $K \in N$ with the following property: For all α -coding sequences a of length $L \geq K$

$$|B_a(I, \mu, \delta, N)| > \exp [(\tilde{h}(\mu) - \varepsilon)N], \quad N \geq L.$$

Proof. By (3.1) we can find an $M \in N$ such that

$$(1) \quad |A(I, \mu, \delta/2, N)| > \exp [(\tilde{h}(\mu) - \varepsilon)N], \quad N \geq M.$$

We claim that any $K \in N$ such that

$$(2) \quad K > 4(M + I)\varepsilon^{-1}\delta^{-1}n$$

has the property that is stated in the lemma. Indeed, if a is an α -coding sequence of length L then with $\beta \neq \alpha$

$$(3) \quad B_a(I, \mu, \delta, N) \supset A(I, \mu, \delta, N) \cap \{x \in \Omega^{N-I+1} : x_{k(L-2)} = \beta, 1 \leq k \leq (N+I-1)(L-2)^{-1}\}.$$

If $L \geq K$, then $L - 2 - I > M$. Hence, by (1), (2) and (3),

$$\begin{aligned} |B_a(I, \mu, \delta, N)| &> \exp [(\tilde{h}(\mu) - \varepsilon)(1 - \varepsilon\tilde{h}(\mu)^{-1})N] \\ &> \exp [(\tilde{h}(\mu) - 2\varepsilon)N]. \end{aligned} \quad \text{Q.E.D.}$$

We set for $I, N \in N$

$$\mathfrak{R}(I, N) = \left\{ k = (k_a)_{a \in \Omega^I} \in Z^{n^I} : k_a > 0, a \in \Omega^I, \sum_{a \in \Omega^I} k_a = N \right\},$$

and for $k \in \mathfrak{R}(I, N)$

$$\begin{aligned} \tilde{h}(k) &= \tilde{h}((N^{-1}k_a)_{a \in \Omega^I}), \\ C(I, N, k) &= \{x \in \Omega^{N+I-1} : k_a = N\lambda_x^{(I)}(a), a \in \Omega^I\}. \end{aligned}$$

(3.3) LEMMA. For all $k \in \mathfrak{R}(I, N)$

$$|C(I, N, k)| < \exp (\tilde{h}(k)N) \prod_{a \in \Omega^I} \left(\frac{N}{k_a} \right)^{1/2}.$$

Proof. It is

$$\begin{aligned} |C(I, N, k)| &\leq n^{I-1} \prod_{a \in \Omega^{I-1}} \frac{\left(\sum_{\alpha \in \Omega} k_{(a_1, \dots, a_{I-1}, \alpha)} \right)!}{\prod_{\alpha \in \Omega} k_{(a_1, \dots, a_{I-1}, \alpha)}!} \\ &= n^{I-1} \prod_{a \in \Omega^{I-1}} \left(\sum_{\alpha \in \Omega} k_{(a_1, \dots, a_{I-1}, \alpha)} \right)! \left(\prod_{b \in \Omega^I} k_b! \right)^{-1}. \end{aligned}$$

The lemma follows from this by an application of Stirling's formula. Q.E.D.

Denote

$$X_a = \{x \in \Omega^{\mathbb{Z}} : S^i x \in Z_a, S^{-j} x \in Z_a, \text{ for infinitely many } i, j \in \mathbb{N}\}, \quad a \in \Omega^I, I \in \mathbb{N}.$$

(3.4) THEOREM. Let μ be an ergodic shift-invariant probability measure on $\Omega^{\mathbb{Z}}$ such that

$$\mu(Z_a) > 0, \quad a \in \Omega^I, \quad I \in \mathbb{N},$$

and let $\nu \in \mathfrak{M}_I$, $I \in \mathbb{N}$, $\tilde{h}(\nu) \geq h(\mu)$. Let $\varepsilon > 0$. Then there exist coding sequences b and c and a homeomorphism $U: X_b \rightarrow X_c$ that commutes with the shift, such that

$$|\mu(U^{-1}Z_a) - \nu(a)| < \varepsilon, \quad a \in \Omega^I.$$

Proof. We remark first that we can restrict attention to the case $h(\mu) < \tilde{h}(\nu)$. Indeed, if $h(\mu) = \log n$, then

$$\mu(Z_a) = \nu(a), \quad a \in \Omega^I,$$

and if $h(\mu) = \tilde{h}(\nu) < \log n$, then there is a $\nu' \in \mathfrak{M}_I$ such that

$$h(\mu) < \tilde{h}(\nu'),$$

and $|\nu'(a) - \nu(a)| < \varepsilon/2$, $a \in \Omega^I$.

Let therefore

$$4\xi = \tilde{h}(\nu) - h(\mu) > 0.$$

We choose an $I' \geq I$ such that $\tilde{h}(\nu) - \tilde{h}(\mu') < \xi$, where $\mu'(a) = \mu(Z_a)$, $a \in \Omega^{I'}$. Let

$$(4) \quad 6\varepsilon' = n^{I-I'}\varepsilon.$$

Let also

$$\nu'(a) = \hat{\nu}(Z_a), \quad a \in \Omega^{I'}.$$

We set $2\delta = \min_{a \in \Omega^{I'}} \mu(Z_a)$ and

$$F_N = \left\{ x \in \Omega^{N+I'-1} : h(\lambda_x^{(I')}) - h(\mu) < 2\xi, \min_{a \in \Omega^{I'}} \lambda_x^{(I')}(a) > \delta \right\}, \quad N > I'.$$

As a consequence of the individual ergodic theorem there is an $M \in \mathbb{N}$ such that

$$(5) \quad \mu \left(\bigcap_{M'=-M}^{M'} \{x \in \Omega^{\mathbb{Z}} : (x_i)_{i=M'}^{M'} \in F_{M'-M''-I'+2}\} \right) > 1 - \varepsilon'.$$

By (3.2) we can also find an $L \in N$, $L \geq n$, such that for all γ -coding sequences c of length $L' \geq L$

$$(6) \quad |B_c(I', \nu', \varepsilon', N)| > \exp[(h(\nu) - \xi)N], \quad N \geq L'.$$

Let further $J \in N$, $J > \xi^{-1}$, be such that

$$(7) \quad J^{-n'} \delta^{(n'/2)} \exp(J\xi) > 1.$$

We choose now a $K \geq L$ and $\alpha_1, \dots, \alpha_K \in \Omega$ such that

$$(8) \quad (I' + M + J + K)n^{-K} < \varepsilon',$$

and

$$(9) \quad \mu(Z_{(\alpha_i)_{i=1}^K}) < n^{-K}.$$

Let $b \in \Omega^{2K+1}$ be the coding sequence that is given by

$$\begin{aligned} b_k &= \alpha_k, & \text{if } 1 \leq k \leq K, \\ &= \alpha_1, & \text{if } k = K+1, \\ &= \gamma \neq \alpha_1, & \text{if } K+1 < k \leq 2K+1, \end{aligned}$$

and set

$$Y = \Omega^Z - \bigcup_{i=1}^{2K+1} S^i Z_b.$$

We have from (8) and (9)

$$(10) \quad \mu(Y) > 1 - 2\varepsilon'.$$

We define for $x \in Y$

$$i^+(x) = \min\{i \geq 0 : S^i x \in Z_b\}, \quad i^-(x) = \min\{i \geq 0 : S^{-i-2K-2} x \in Z_b\}.$$

(3.3) together with (6) and (7) implies that for a γ -coding sequence c of length $2K+1$

$$\begin{aligned} |B_c(I', \nu', \varepsilon', N)| |F_N|^{-1} &> \exp[(h(\nu) - \xi)N] N^{-n'} \delta^{(n'/2)} \exp[-(h(\mu) + 2\xi)N] \\ &= N^{-n'} \delta^{(n'/2)} \exp(\xi N) > 1, \quad N \geq J + 2K + 1. \end{aligned}$$

We see now that there are mappings φ_N , $N \in N$, of Ω^N onto itself such that

$$\varphi_{N+I'-1}(\{a \in F_N : (a_i)_{i=l}^{l+2K} \neq b, 1 \leq l \leq N+I'-2K\}) \subset B_c(I', \nu', \varepsilon', N),$$

$$N \geq J + 2K + 1,$$

and such that

$$\begin{aligned} \varphi_N(\{a \in \Omega^N : (a_i)_{i=l}^{l+2K} \neq b, 1 \leq l \leq N-2K\}) \\ = \{a \in \Omega^N : (a_i)_{i=l}^{l+2K} \neq c, 1 \leq l \leq N-2K\}, \quad N \geq 2K+1. \end{aligned}$$

We define now a homeomorphism $U: X_b \rightarrow X_c$, that commutes with S by setting for $x \in Z_b \cap X_b$, $Ux=y$, where

$$y_i = c_i, \quad 1 \leq i \leq 2K+1$$

$$(y_i)_{i=-i^-(x)}^0 = \varphi_{i^-(x)+1}(x_i)_{i=-i^-(x)}^0.$$

To conclude the proof of the theorem we use (5), (8), (9) and (10) to get

$$\begin{aligned} \mu(\{x \in Y : i^+(x) + i^-(x) \geq J+2K, i^+(x) \geq I'-1, (x_i)_{i=-i^-(x)}^{i^+(x)} \in F_{i^+(x)+i^-(x)-I'+2}\}) \\ > \mu(\{x \in Y : i^+(x), i^-(x) \geq I'+M+J+K\}) - \varepsilon' \\ > 1 - 2(I'+M+J+K)n^{-K} - 3\varepsilon' \\ > 1 - 5\varepsilon'. \end{aligned}$$

We infer from this by applying the individual ergodic theorem that

$$(\nu'(a) - \varepsilon')(1 - 5\varepsilon') < \mu(U^{-1}Z_a) < \nu'(a) + 6\varepsilon', \quad a \in \Omega^{I'}.$$

Finally by (4)

$$|\mu(U^{-1}Z_a) - \nu(a)| < \varepsilon, \quad a \in \Omega^I. \quad \text{Q.E.D.}$$

We want to point out the following consequence of (3.4). Let

$$X = \bigcap_{I=1}^{\infty} \bigcap_{a \in \Omega^I} X_a,$$

and let $\mathfrak{M}_h$ be the set of shift-invariant ergodic probability measures μ on $\Omega^{\mathbb{Z}}$ such that $\mu(Z_a) > 0$, $a \in \Omega^I$, $I \in \mathbb{N}$, and $\mu(X) = 1$, $h(\mu) = h$, $0 \leq h \leq \ln n$.

The $\mathfrak{M}_h$ with the weak topology are polish spaces. The group $\mathcal{G}$ of homeomorphisms of X that commute with the shift acts on $\mathfrak{M}_h$ by $\mu \rightarrow U\mu$, $\mu \in \mathfrak{M}_h$, $U \in \mathcal{G}$, where

$$U\mu(Z_a) = \mu(U^{-1}Z_a), \quad a \in \Omega^I, \quad I \in \mathbb{N}.$$

The homeomorphism that we have constructed in the proof of (3.4) maps X onto X . It follows therefore from (3.4) that the transformation groups $(\mathcal{G}, \mathfrak{M}_h)$ are minimal, $0 \leq h \leq \ln n$.

4. An estimate for Δ .

(4.1) LEMMA. *For every ergodic shift-invariant probability measure μ on $\Omega^{\mathbb{Z}}$ there exists a shift-invariant probability measure ν on $\Omega^{\mathbb{Z}}$ such that for all $a \in \Omega^I$, $I \in \mathbb{N}$, $\nu(Z_a) > 0$, and such that the systems $(\Omega^{\mathbb{Z}}, \mu, S)$ and $(\Omega^{\mathbb{Z}}, \nu, S)$ are isomorphic.*

Proof. If there is a $d \in \bigcup_{I=1}^{\infty} \Omega^I$, such that $\mu(Z_d) = 0$, then we can assign in a 1-1 manner to every $a \in \bigcup_{I=1}^{\infty} \Omega^I$ a coding sequence $b(a)$ that contains a as a subsequence such that $\mu(Z_{b(a)}) = 0$. Let $L(a)$ be the length of $b(a)$. We can find Borel sets $A_a \subset \Omega^{\mathbb{Z}}$ such that for all $a, a' \in \bigcup_{I=1}^{\infty} \Omega^I$

$$\mu(S^l A_a \cap S^{l'} A_a) = 0, \quad 0 \leq l, l' \leq 2L(a),$$

and

$$\mu\left(\left(\bigcup_{l=0}^{2L(a)} S^l A_a\right) \cap \left(\bigcup_{l=0}^{2L(a')} S^{l'} A_{a'}\right)\right) = 0.$$

Choose $c(a) \in \Omega^{L(a)}$ such that $\mu(Z_{c(a)} \cap A_a) > 0$.

A Borel mapping $U: \Omega^{\mathbb{Z}} \rightarrow \Omega^{\mathbb{Z}}$ that commutes with the shift can be defined by

$$(Ux)_i = x_i, \quad \text{if } S^i x \notin \bigcup_{l=1}^{\infty} \bigcup_{a \in \Omega^l} (Z_{c(a)} \cap A_a),$$

and

$$Ux \in Z_{c(a)}, \quad \text{if } x \in Z_{c(a)} \cap A_a, \quad a \in \Omega^l, \quad l \in \mathbb{N}.$$

Setting for a Borel set $F \in \Omega^{\mathbb{Z}}$, $\nu(F) = \mu(U^{-1}F)$ proves the lemma. Q.E.D.

(4.2) LEMMA. *Let T be an ergodic i.m.p.t. of $(E, \mathfrak{B}, p)$ with a generator*

$$\{A_0, \dots, A_m\}, \quad m > 1,$$

such that

$$p(A_0) > p(A_1) + 2p(A_2).$$

Then $\Delta(T) \leq m$.

Proof. This lemma follows from a slightly generalized version of a theorem of A. H. Zaslavskii [7, p. 295]. Q.E.D.

(4.3) THEOREM. *Let T be an ergodic i.m.p.t. Then $\Delta(T) \leq e^{h(T)} + 1$.*

Proof. By (2.1) there exist a state space $\Omega = \{0, \dots, m\}$, $m \in \mathbb{N}$, and a shift-invariant probability measure μ on $\Omega^{\mathbb{Z}}$ such that T is isomorphic to the system $(\Omega^{\mathbb{Z}}, \mu, S)$. By (4.1) we can assume here that $\mu(Z_a) > 0$, $a \in \Omega^l$, $l \in \mathbb{N}$. If now $m > e^{h(T)}$, then we can find a q , $0 < q < (2m)^{-1}$ such that

$$h((\lambda_k)_{k=0}^m) > h(T),$$

where

$$\lambda_0 = n^{-1} + q, \quad \lambda_1 = n^{-1} - 2q, \quad \lambda_2 = q, \quad \lambda_k = n^{-1}, \quad 2 < k \leq m.$$

From (3.4) we see now that there is a shift-invariant probability measure ν on $\Omega^{\mathbb{Z}}$ such that $(\Omega^{\mathbb{Z}}, \mu, S)$ is isomorphic to $(\Omega^{\mathbb{Z}}, \nu, S)$ and such that

$$|\nu(Z_{(k)}) - \lambda_k| < q/4, \quad 1 \leq k \leq m.$$

It is then

$$\nu(Z_{(0)}) > \nu(Z_{(1)}) + 2\nu(Z_{(2)})$$

and the theorem follows by means of (4.2). Q.E.D.

(4.4) COROLLARY. *Let T be the cartesian product of the n -shift with entropy $\ln n$, $n \geq 2$, and an ergodic i.m.p.t. with entropy zero. Then $\Delta(T) = n + 1$.*

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