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An answer to a question by J. Milnor

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We consider two commuting automorphisms T_1, T_2 of the Lebesque space $(M, \mathcal{M}, \mu)$ such that $h_{m,n} = h(T_1^m T_2^n) < \infty$ where h is the measure-theoretic entropy. Under additional assumptions we show the existence of the limits $\lim (1/m)h_{m,n}$ where $m \to \infty$, $n \to \infty$, $m/n \to \omega$ and ω is an irrational number.

§1. Formulation of the problem and the result

Let $X = \{x^{(1)}, \ldots, x^{(\kappa)}\}$ be a finite alphabet and M be the space of double-infinite sequences $x = \{x_n\}_{-\infty}^{\infty}$, $x_n \in X$, S is the shift in M, i.e. $Sx = x' = \{x'_n\}$, $x'_n = x_{n+1}$. Then M is a compact topological space in topology of direct product and S is a homeomorphism of M. Assume that a function $f(x_{-r}, \ldots, x_r)$ with values in X is given. It generates a homomorphism T of M by the formula: $Tx = y = \{y_n\}_{-\infty}^{\infty}$, $y_n = f(x_{n-r}, \ldots, x_{n+r})$. S and T commute and we assume that they generate an action of the group $\mathbb{Z}^2$ on M: for $(m, n) \in \mathbb{Z}^2$ the corresponding transformation is $T_{m,n} = S^m T^n$. The described situation was considered by Professor J. Milnor in his talk "Cellular automata as discrete dynamical systems" during the celebration of the 20-th anniversary of the Forschungsinstitut fur Mathematik, ETH in Zurich. He formulated the following question. Assume that μ is a normed ergodic measure invariant under the action of $\mathbb{Z}^2$. Denote $h_{m,n} = h(S^m T^n)$ measure-theoretic entropy of $T_{m,n}$ with respect to μ. It is easy to show that $h_{m,0} < \infty$ for all $-\infty < m < \infty$. We shall consider the case when $h_{m,n} < \infty$ for all $-\infty < m, n < \infty$. From the properties of entropy (see [1]) it follows that the function $h_{m,n}$ is an homogeneous function of the first degree, i.e. $h_{\kappa m, \kappa n} = |\kappa|\, h_{m,n}$. Fix an irrational number $\omega_0 > 0$ and choose a sequence $(m_i, n_i) \in \mathbb{Z}^2$, $m_i \to \infty$, $n_i \to \infty$, $m_i/n_i \to \omega_0$ as $i \to \infty$. The question is whether there exists a limit $\lim_{i\to\infty} (1/\sqrt{m_i^2 + n_i^2}) h_{m_i,n_i}$ which can be called as entropy per unit of length in the direction ω_0. The aim of this paper is to give an affirmative answer to this question. It will be more convenient to show the existence of the limit $\lim_{i\to\infty} (1/n_i) h_{m_i,n_i}$ which is equivalent to the first one.

We introduce the partition ξ into κ sets C_κ, $1 \le i \le \kappa$, $C_i = \{x \mid x_0 = x^{(i)}\}$, $\xi_{m,n} = T_{m,n}\xi$. We shall use later standard notations and facts of the theory of measurable partitions and measure-theoretic entropy (there are many good references, we shall mention only few of them, [1], [2], [3]). By $I=I(a,\omega)$ we denote the segment on the plane joining the points $(a,0)$ and $(a+\omega^{-1},1)$ and $\Gamma(a,\omega)$ is the half-line $y=\omega(x-a)$, $y\leq 1$. It is clear that $I(a,\omega)\subset\Gamma(a,\omega)$. We shall always consider the case $\omega>0$. The main role in our analysis play the conditional entropies

$$\mathcal{H}_r(I)=H\Big(\bigvee_{m\geq a+\omega^{-1}}\xi_{m,1}\,\Big|\,\bigvee_{n=0}^{\infty}\bigvee_{m\geq a+\omega^{-1}n}\xi_{m,-n}\Big)$$

$$\mathcal{H}_l(I)=H\Big(\bigvee_{m\leq a+\omega^{-1}}\xi_{m,1}\,\Big|\,\bigvee_{n=0}^{\infty}\bigvee_{m\leq a+\omega^{-1}n}\xi_{m,-n}\Big)$$

$$\mathcal{H}(I)=\mathcal{H}_r(I)+\mathcal{H}_l(I).$$

It is easy to see that both $\mathcal{H}_r(I)$, $\mathcal{H}_l(I)$ are finite. We shall list three properties of them which will be used later:

1. $\mathcal{H}_r(I)$, $\mathcal{H}_l(I)$ are periodic functions of a with the period 1 for each fixed ω;

2. if ω is a rational number, $\omega=p/q$, then $\mathcal{H}_r(I)$, $\mathcal{H}_l(I)$ are constants on each interval of a of the length $1/p$ where the half-lines $\Gamma(a,\omega)$ do not pass through points of the lattice $\mathbb{Z}^2$.

3. if ω is irrational and $\Gamma(a,\omega)$ does not pass through points of the lattice $\mathbb{Z}^2$ then $\mathcal{H}_r(I)$, $\mathcal{H}_l(I)$ are continuous at the point (a,ω).

The last property follows easily from the properties of continuity of conditional entropy. We shall use also a transformation Q in the space of segments $I(a,\omega)$, where $Q(I(a,\omega))=I(a',\omega)$, $a'=a+\omega^{-1}$.

Our first result is the following theorem.

THEOREM 1. *Let $p>0$, $q>0$ have no common factor. Then $h_{p,q}=\sum_{i=0}^{p-1}\mathcal{H}(Q^i(I))=p\int_0^1\mathcal{H}(I)\,da$ for any interval $I=I(a,-q/p)$.*

The proof of Theorem 1 is given in §2.

THEOREM 2. *Let ω_0 be an irrational number, (m_i,n_i) be a sequence of points of the lattice $\mathbb{Z}^2$, $m_i, n_i\to\infty$ and $m_i/n_i\to\omega_0$ as $i\to\infty$. Then*

$$\lim_{i\to\infty}\frac{1}{n_i}h_{m_i,n_i}=\int_0^1\mathcal{H}(I(a,\omega_0))\,da.$$

Proof of Theorem 2. We have from Theorem 1

$$\frac{1}{n_i} h_{m_i,n_i} = \int_0^1 \mathcal{H}(I(a, m_i/n_i))\, da.$$

All functions $\mathcal{H}(I(a, m_i/n_i))$ are uniformly bounded and non-negative. It follows from the property 3 that for almost every a

$$\lim_{i\to\infty} \mathcal{H}(I(a, m_i/n_i)) = \mathcal{H}(I(a, \omega_0)).$$

Thus in view of Lebesgue dominance theorem we have the desired result. Q.E.D.

In §3 we make some additional remarks.

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§2. Proof of Theorem 1

It follows from the properties of measure-theoretic entropy that

$$h_{q,p} = \lim_{s\to\infty} H\Bigg(\bigvee_{n=1}^{p} \bigvee_{a+\omega^{-1}n-s\le m\le a+\omega^{-1}n+s} \xi_{m,n} \Bigg| \bigvee_{n\le 0} \bigvee_{a+\omega^{-1}n-s\le m\le a+\omega^{-1}n+s} \xi_{m,n} \Bigg), \qquad \omega = q/p.$$

The last conditional entropy is equal to

$$\sum_{l=1}^{p} H\Bigg(\bigvee_{a+\omega^{-1}l-s\le m\le a+\omega^{-1}l+s} \xi_{m,l} \Bigg| \bigvee_{n<l} \bigvee_{|m-a-\omega^{-1}n|\le s} \xi_{m,n} \Bigg)$$

$$= \sum_{l=1}^{p} H\Bigg(\bigvee_{a+\omega^{-1}l-s\le m\le a+\omega^{-1}l+s} \xi_{m,1} \Bigg| \bigvee_{n<0} \bigvee_{|m-a-\omega^{-1}n|\le s} \xi_{m,n} \Bigg).$$

We shall show that the l-th term converges as $s \to \infty$ to $\mathcal{H}(Q^l(I))$. It is sufficient to consider $l = 1$, other terms are treated in the same way. From the description of our system it follows easily that

$$H\Big(\bigvee_{a+\omega^{-1}-s\leq m\leq a+\omega^{-1}+s}\xi_{m,1}\Big|\bigvee_{n\leq 0}\ \bigvee_{a+\omega^{-1}n-s\leq m\leq a+\omega^{-1}n+s}\xi_{m,n}\Big)$$

$$=H\Big(\bigvee_{a+\omega^{-1}-s\leq m\leq a+\omega^{-1}-s+r}\xi_{m,1}\vee\bigvee_{a+\omega^{-1}+s-r\leq m\leq a+\omega^{-1}+s}\xi_{m,1}\Big|$$
$$\bigvee_{n\leq 0}\ \bigvee_{a+\omega^{-1}n-s\leq m\leq a+\omega^{-1}n+s}\xi_{m,n}\Big)$$

$$=H\Big(\bigvee_{a+\omega^{-1}+s-r\leq m\leq a+\omega^{-1}+s}\xi_{m,1}\Big|\bigvee_{n\leq 0}\ \bigvee_{a+\omega^{-1}n-s\leq m\leq a+\omega^{-1}n+s}\xi_{m,n}\Big)$$
$$+H\Big(\bigvee_{a+\omega^{-1}-s\leq m\leq a+\omega^{-1}-s+r}\xi_{m,1}\Big|\bigvee_{a+\omega^{-1}+s-r\leq m\leq a+\omega^{-1}+s}\xi_{m,1}$$
$$\times\bigvee_{n\leq 0}\ \bigvee_{a+\omega^{-1}n-s\leq m\leq a+\omega^{-1}n+s}\xi_{m,n}\Big)\qquad(1)$$

The first term in (1) is equal to

$$H\Big(\bigvee_{a+\omega^{-1}-[a+\omega^{-1}]-r\leq m\leq a+\omega^{-1}-[a+\omega^{-1}]}\xi_{m,1}\Big|\bigvee_{n\leq 0}\ \bigvee_{a+\omega^{-1}n-2s-[a+\omega^{-1}]\leq m\leq a+\omega^{-1}n-[a+\omega^{-1}]}\xi_{m,n}\Big)$$

It follows from the properties of continuity of conditional entropy that this expression converges to $\mathscr{H}_l(I)$. We shall show that the second term in (1) converges to $\mathscr{H}_r(I)$. We have

$$H\Big(\bigvee_{a+\omega^{-1}-s\leq m\leq a+\omega^{-1}-s+r}\xi_{m,1}\Big|\bigvee_{a+\omega^{-1}+s-r\leq m\leq a+\omega^{-1}+s}\xi_{m,1}$$
$$\vee\bigvee_{n\leq 0}\ \bigvee_{a+\omega^{-1}n-s\leq m\leq a+\omega^{-1}n+s}\xi_{m,n}\Big)$$
$$=H\Big(\bigvee_{a+\omega^{-1}-[a+\omega^{-1}]\leq m\leq a+\omega^{-1}-[a+\omega^{-1}]+r}\xi_{m,1}\Big|\bigvee_{a+\omega^{-1}+2s-r-[a+\omega^{-1}]\leq m\leq a+\omega^{-1}-[a+\omega^{-1}]+2s}\xi_{m,1}$$
$$\vee\bigvee_{n\leq 0}\ \bigvee_{a+\omega^{-1}(n+1)-[a+\omega^{-1}]\leq m\leq a+\omega^{-1}(n+1)-[a+\omega^{-1}]+2s}\xi_{m,n}\Big).$$

We denote

$$\eta=\bigvee_{a+\omega^{-1}-[a+\omega^{-1}]\leq m\leq a+\omega^{-1}-[a+\omega^{-1}]+r}\xi_{m,1}$$

and $C_\eta(x)$ is an element containing $x \in M$. Also let us introduce the partitions

$$\zeta_s = \bigvee_{a+\omega^{-1}-[a+\omega^{-1}]\leq m\leq a+\omega^{-1}-[a+\omega^{-1}]+r+2s} \xi_{m,0}$$

$$\vee \bigvee_{n<0} \bigvee_{a+\omega^{-1}(n+1)-[a+\omega^{-1}]\leq m\leq a+\omega^{-1}(n+1)-[a+\omega^{-1}]+2s} \xi_{m,n},$$

$$\zeta^+ = \bigvee_{n\leq 0} \bigvee_{a+\omega^{-1}(n+1)-[a+\omega^{-1}]\leq m} \xi_{m,n}$$

In view of Doob's theorem on convergence of conditional probabilities

$$\mu(C_\eta(x) \mid C_{\zeta_s}(x)) \to \mu(C_\eta(x) \mid C_{\zeta^+}(x)) \quad \text{a.e.,}$$

where $C_{\zeta_s}(x)$, $C_{\zeta^+}(x)$ are elements of corresponding partitions containing x. But

$$\mu\Big(C_\eta(x) \Big| \bigvee_{a+\omega^{-1}+2s-r-[a+\omega^{-1}]\leq m\leq a+\omega^{-1}-[a+\omega^{-1}]+2s} \xi_{m,1}$$

$$\vee \bigvee_{n\leq 0} \bigvee_{a+\omega^{-1}(n+1)-[a+\omega^{-1}]\leq m\leq a+\omega^{-1}(n+1)-[a+\omega^{-1}]+2s} \xi_{m,n}\Big) \quad (2)$$

can be represented as finite linear combinations of $\mu(C_\eta(x) \mid C_{\zeta_s}(x))$. This shows easily that the conditional probabilities (2) also converge a.e. as $s \to \infty$ to $\mu(C_\eta(x) \mid C_{\zeta^+}(x))$. This gives the desired result. Q.E.D.

§3. Several general remarks

Let us consider two commuting automorphisms T_1, T_2 of Lebesgue space $(M, \mathcal{M}, \mu)$. Then we have a measure-preserving action of the group $\mathbb{Z}^2$ on M and we shall assume that it is ergodic and at least one of automorphisms T_1, T_2 is also ergodic. Without any loss of generality we can assume T_1 is ergodic. If the measure-theoretic entropy $h(T_1)$ is finite one can find a finite generating partition $\xi = \{C_1, \ldots, C_\kappa\}$ in view of Krieger's theorem [4]. It means that T_1 is isomorphic to the shift in the space of doubly-infinite sequences written in the alphabet of κ symbols. If $T_2 x = y = \{y_n\}$ then $y_n = f(x_n, x_{n\pm1}, x_{n\pm2}, \ldots)$ where f is a measurable function with the values in the space $\{1, 2, \ldots, \kappa\}$. Thus the pair (T_1, T_2) is represented as a system of cellular automata but maybe with an infinite memory. Our arguments presented above can be extended to the case when f can be approximated sufficiently well by functions of finite number of variables. However, the general case remains completely open. One can mention also an interesting paper by G. A. Galperin [5] where some results concerning topological entropy of systems of cellular automata were established.

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Added in proof:

It is clear that theorems 1 and 2 are easily generalized to the case of non-ergodic measures. Indeed, if ν_{inv} is the measurable partition of M into ergodic components of the action of $\mathbb{Z}^2$ corresponding to the measure μ, then

$$\frac{1}{n} h_{m,n} = \int_{M \mid \nu_{\text{inv}}} \frac{1}{n} h(S^m T^n \mid C_{\nu_{\text{inv}}})\, d\mu_{\text{inv}}$$

where μ_{inv} is the induced measure on the factor-space $M \mid \nu_{\text{inv}}$. We showed already for a.e. element $C_{\nu_{\text{inv}}}$ of ν_{inv} the convergence of $(1/n)h(S^m T^n \mid C_{\nu_{\text{inv}}})$, $(m/n) \to \omega$, which implies the convergence of $(1/n)h_{m,n}$.

Also in the same way one can consider the action of the semi-group $\mathbb{Z}^2_+ = \{(m, n): -\infty < m < \infty, n \geq 0\}$. In order to get the assertions of theorems 1 and 2 one should replace possible pasts by possible futures in all arguments.