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A LITTLE TOPOLOGICAL COUNTERPART OF BIRKHOFF'S ERGODIC THEOREM

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ABSTRACT. For a compact metric space X and a continuous transformation $T : X \to X$ with at least one transitive and recurrent orbit, there is a set $M_0(T)$ of T-invariant probability measures on X such that for a comeager set of starting points the set of limit measures is exactly $M_0(T)$.

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1. Introduction

For a compact metric space X and $T : X \to X$ a point $x \in X$ is called transitive, resp. recurrent if its T-orbit $(T^n x)_{n\in\mathbb{N}}$ is dense resp. meets every neighbourhood of x infinitely many times. Furthermore $\mathcal{M}(X, T)$ denotes the set of those $\mu \in \mathcal{M}(X)$ (the compact metrizable space of all Borel probability measures) which are T-invariant, and $M(T, x)$ is the set of all limit measures of the sequence $\mathbf{x} = (x_n)_{n\in\mathbb{N}}$ with $x_n = T^n x$. By definition, a limit measure of $\mathbf{x}$ is an accumulation point of the measures $\mu_{\mathbf{x},n} = \frac{1}{n}\sum_{k=0}^{n-1}\delta_{x_k} \in \mathcal{M}(X)$, $n = 1, 2, 3, \dots$, δ_{x_k} denoting the point measures concentrated in $x_k \in X$. We will prove:

Theorem. *Let X be a compact metric space, $T : X \to X$ a continuous transformation, $x_0 \in X$ a transitive and recurrent point and $M_0(T)$ the union of all $M(T, x)$ with transitive x. Then $M(T, x) = M_0(T)$ for most $x \in X$, i.e., for all $x \in X \setminus E$ where the exceptional set E is meager (of first Baire category).*

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Note that for infinite X the assumptions of the Theorem imply that X is perfect (i.e., has no isolated points), hence uncountable, and that every dense orbit is recurrent.

For an ergodic measure $\mu \in \mathcal{M}(X,T)$, Birkhoff's ergodic theorem yields that for μ-almost all $x \in X$ the sequence $\mathbf{x} = (T^n x)_{n\in\mathbb{N}}$ is uniformly distributed with respect to μ, i.e., $M(T,x) = \{\mu\}$. Thus the Theorem above can be considered as a topological counterpart in the sense of Baire categories (see also the classical textbook [O 80]) where the singleton $\{\mu\}$ has to be replaced by the set $M_0(T)$. The proof of the Theorem is the content of Section 2. Section 3 is a short discussion including examples where $M_0(T) = \mathcal{M}(X,T)$, i.e., where most points have maximal oscillation in the sense of (21.17) in [DGS 76]. Section 4 shows that $M_0(T) \neq \mathcal{M}(X,T)$ is possible as well.

Related properties of the topologically typical distribution behaviour of orbits have already been observed in [D 53], for arbitrary sequences by Prof. Hlawka in his seminal paper [H 56]. For more recent investigations cf. [Wi 97], [GSW 00], [GSW 07] and [TZ 10].

2. Proof of the Theorem

Let in this Section X, T and x_0 be as in the assumptions of the Theorem. For any sequence of mappings $\phi_n : X \to Y$ (Y metric space) and $y \in Y$ the set $X\big((\phi_n), y\big)$ of all $x \in X$ such that y is an accumulation point of $\big(\phi_n(x)\big)_{n\in\mathbb{N}}$ can be written as

$$X\big((\phi_n), y\big) = \bigcap_{N,k\in\mathbb{N}} \bigcup_{n\geq N} \phi_n^{-1}\left(B\Big(y, \frac{1}{k+1}\Big)\right).$$

($B(y,r)$ denotes the open ball with center y and radius r.) For any topological space X and continuous ϕ_n the sets $\phi_n^{-1}\big(B(y, \frac{1}{k+1})\big)$ are open. This shows that for continuous $\phi_n : X \to Y$, $X\big((\phi_n), y\big)$ is a G_δ-set and that $X\big((\phi_n), y\big)$ is residual if and only if for all $N, k \in \mathbb{N}$ the set

$$\bigcup_{n\geq N} \phi_n^{-1}\left(B\Big(y, \frac{1}{k+1}\Big)\right)$$

is dense in X. Take

$$Y = \mathcal{M}(X), \quad \phi_n : x \mapsto \mu_{(T^k x)_{k\in\mathbb{N}}, n} = \frac{1}{n}\sum_{k=0}^{n-1} \delta_{T^k x} \quad \text{and} \quad y = \mu \in M(T, x_0).$$

Since then $\mu \in M\big(T, T^n(x_0)\big)$ for all $n \in \mathbb{N}$, $\bigcup_{n \geq N} \phi_n^{-1}\big(B(\mu, \frac{1}{k+1})\big)$ is dense in X for all $N, k \in \mathbb{N}$ (the balls taken w.r.t. any metric for the topology on $\mathcal{M}(X)$). Hence:

Proposition 1. *If $\mu \in M(T, x_0)$, then $\mu \in M(T, x)$ for most $x \in X$.*

As a subset of the compact metric space $\mathcal{M}(X)$, $M_0(T)$ contains a countable dense subset $\{\mu_n : \ n \in \mathbb{N}\}$. Let X_{μ_n} denote the set of all $x \in X$ with $\mu_n \in M(T, x)$. By Proposition 1 each X_{μ_n}, $n \in \mathbb{N}$, is residual in X. Hence also the countable intersection $X_1 = \bigcap_{n \in \mathbb{N}} X_{\mu_n}$ is residual. For all $x \in X_1$ and $n \in \mathbb{N}$ we have $\mu_n \in M(T, x)$. Since $M(T, x)$ is closed this implies:

Proposition 2. *$M_0(T) \subseteq \overline{M(T)} \subseteq M(T, x)$ for most $x \in X$.*

It is well-known that in transitive systems most orbits are dense (cf. for instance [DGS 76], 6.11). By the definition of $M_0(T)$ as the union of the $M(T, x)$ with transitive x and since $M(T, x) \subseteq \mathcal{M}(X, T)$ (cf. for instance [GSW 07], Lemma 2.17 (1)) this implies the converse inclusion $M(T, x) \subseteq M_0(T)$ for most $x \in X$, proving the Theorem.

3. Discussion

Trivial examples for the Theorem are uniquely ergodic transformations where $M_0(T) = \mathcal{M}(X, T)$ is a singleton. A less trivial example with $M_0(T) = \mathcal{M}(X, T)$ is the full shift, i.e., $X = A^{\mathbb{N}}$, the set of all sequences over a finite alphabet A, and $T = \sigma : x = (a_n)_{n \in \mathbb{N}} \mapsto (a_{n+1})_{n \in \mathbb{N}}$ (cf. [DGS 76] chapter 21, in particular 21.18). The full shift also shows that the residual set of all $x \in X$ with $M(T, x) = M_0(T)$, in general, does not coincide with the set of all transitive and recurrent x: Take any sequence x which contains all finite words, separated by sufficiently long blocks of 0's. Then $M(T, x) = \{\delta_{0^\infty}\} \neq \mathcal{M}(X, T) = M_0(T)$, while x is transitive and recurrent.

It is clear that the transitivity assumption in the Theorem cannot be omitted. (Otherwise, we might have disjoint open sets with disjoint T-orbits such that the Theorem must fail. Most trivial example: T the identity on X where X contains at least two points.) However, some kind of generalization of the Theorem to the intransitive case is possible. But since this requires a much broader framework, I do not go into this direction here.

Similarly to the transitivity assumption, the Theorem does not hold, in general, if we omit the recurrence condition. Consider $X = X_1 \cup \{x_0\}$, the compact space $X_1 = \{0, 1\}^{\mathbb{N}}$ of all binary sequences plus an isolated point x_0. Let

$T = T_0 \cup T_1$ with the shift $T_1 = \sigma : (a_n)_{n\in\mathbb{N}} \to (a_{n+1})_{n\in\mathbb{N}}$ on X_1 and $T_0 : x_0 \mapsto x_1$ with some $x_1 \in X_1$. If x_1 contains each binary word of finite length, then x_0 is a transitive point (but not recurrent). As already mentioned above there is a $M_0(T_1)$, namely the set of all invariant measures on X_1. If x_1 is suitably chosen (see above), then $M(T, x_0) = M(T, x_1)$ does not contain all invariant measures. $\{x_0\}$, as an open set, is not meager. Thus, provided $M(T, x_1) \neq \mathcal{M}(X, T_1)$, there is no Baire-typical $M_0(T)$ for T considered as a transformation on the whole space $X = X_1 \cup \{x_0\}$.

4. An example with $M_0(T) \neq \mathcal{M}(X, T)$

Our example is the subshift generated by the binary sequence

$$x_0 = \mathbf{a} = (a_n)_{n\in\mathbb{N}} = a_0a_1a_2\ldots = 0^1 1^1 a_0 0^2 1^2 a_0 a_1 0^3 1^3 a_0 a_1 a_2 \ldots$$

Let X be the orbit closure of x_0 under σ and T the restriction of σ to X. Note that x_0 is defined in such a way that each finite initial word of x_0 occurs infinitely many times in x_0. Hence x_0 is recurrent. Since X is the orbit closure, x_0 is also transitive. So the Theorem applies and $M(T, x) = M_0(T)$ for most $x \in X$. Note that $1^\infty = 111\ldots \in X$ since x_0 contains all 1-blocks 1^n, $n \in \mathbb{N}$. Furthermore the point measure δ_{1^∞} is shift invariant, hence $\delta_{1^\infty} \in \mathcal{M}(X, T)$. So the proof of $M_0(T) \neq \mathcal{M}(X, T)$ will be complete as soon as we have shown $\delta_{1^\infty} \notin M_0(T)$.

The definition of x_0 induces a partition of $\mathbb{N}$ into subintervals $I_k = I_k^{(0)} \cup I_k^{(1)} \cup I_k^{(r)}$, $k = 1, 2, 3, \ldots$, in such a way that $I_1 < I_2 < \ldots$ elementwise, $I_k^{(0)} < I_k^{(1)} < I_k^{(r)}$ elementwise and $|I_k^{(0)}| = |I_k^{(1)}| = |I_k^{(r)}| = k$. Clearly this determines the partition uniquely. Note that $a_n = 0$ for all $n \in I_k^{(0)}$, $a_n = 1$ for all $n \in I_k^{(1)}$ and $a_n = a_j$ if $n = m + j \in I_k^{(r)} = \{m, m+1, \ldots, m+k-1\}$ with $j < k$.

Let W_l be the set of all words $w = (a'_n, a'_{n+1}, \ldots, a'_{n+l-1})$ of length l occuring in x_0 and $W = \bigcup_{l\in\mathbb{N}} W_l$. Let us write $\mu(0|w)$ and $\mu(1|w) = 1 - \mu(0|w)$ for the relative frequency of 0's, resp. 1's in a nonempty word w. Formally: For $w = (a'_0, \ldots, a'_{l-1})$, $\mu(i|w) = \frac{1}{l}|\{n : \ 0 \leq n \leq l-1, \ a'_n = i\}| \in [0, 1]$, $i \in \{0, 1\}$, $l = 1, 2, \ldots$

Proposition 3. *In every initial word $w = (a_0, a_1, \ldots, a_{l-1})$ of x_0, $l \in \mathbb{N}$, we have $\mu(0|w) \geq \frac{1}{2} \geq \mu(1|w)$.*

Proof of Proposition 3. One sees immediately that the assertion holds for $l = 0, 1, 2, 3$, hence it holds for the word induced by x_0 on I_1, hence on I_2 etc., hence on all concatenations of these finite words. $\square$

Proposition 4. *If $w = 10w' \in W$, then $\mu(0|0w') \geq \frac{1}{2} \geq \mu(1|0w')$.*

Proof of Proposition 4. Let us, by contradiction, suppose that the claim fails. Then there is a minimal $n_0 \in \mathbb{N}$ and an $l \geq 2$ such that

$$w = (a_{n_0}, a_{n_0+1}, \ldots, a_{n_0+l-1}) = 10w'$$

is a counterexample to the proposition. Since $n_0 \notin I_k^{(0)}$ for any $k \in \mathbb{N}$ it suffices to distinguish two cases for n_0.

Case 1. $n_0 \in I_{k_0}^{(1)}$: In the first subcase ($l - 1 \leq k_0$) we have $w = 10w' = 10a_1 \ldots a_{l-1} = 1a_0a_1 \ldots a_{l-1}$, contradicting Proposition 3. In the other subcase ($l - 1 > k_0$) we have $w = 1a_0 \ldots a_{k_0-1}b_{k_0+1}b_{k_0+2} \ldots b_{k_1-1}b_{k_1}$, where the b_j are the finite words induced by x_0 on I_j, b_{k_1} being only an initial segment. This again contradicts Proposition 3.

Case 2. $n_0 \in I_{k_0}^{(r)}$: If (first subcase) $n_0 + l - 1 \in I_{k_0}^{(r)}$, then w occurs already as $w = a_{m_0} \ldots a_{m_0+l-1}$ with $m_0 < n_0$, contradicting the minimal choice of n_0. Otherwise (second subcase) we can write w as a concatenation $w = b_{k_0}b_{k_0+1} \ldots b_{k_1-1}b_{k_1}$ of words b_i with $k_1 > k_0$ in such a way that $b_{k_0} = 10w''$ comes from an end word of $I_{k_0}^{(r)}$, the b_{k_0+j} with $0 < j < k_1 - k_0$ come from the corresponding I_{k_0+j} and b_{k_1} is an initial word. By the minimality of n_0 the claim of the lemma holds for $0w''$ instead of $0w'$. For the tail $b_{k_0+1} \ldots b_{k_1-1}b_{k_1}$ of w, Proposition 3 implies that there are at least as many 0's as 1's, contradiction.

□

Proposition 5. *Every $x = (a'_n)_{n\in\mathbb{N}} \in X$ is either of the form $x = w1^\infty$ (type 1) with a finite initial word w or the upper density $\overline{\mu}(1|x)$ of the set $\{n : a'_n = 1\}$ is at most $\frac{1}{2}$ (type 0). (Here $\overline{\mu}(1|x)$ denotes the upper limit of $\mu(1|w_n)$ for $n \to \infty$, where w_n is the nth initial word of x.) In particular, $\delta_{1^\infty} \notin M(T, x)$ for every x of type 0.*

Proof of Proposition 5. If $x \in X$ is not of type 1, then x contains infinitely many 0's. For $x = 0^\infty$ the claim is obvious, otherwise there is a finite word w_0 and an infinite sequence x' such that $x = w_0 10x'$. For all finite initial words w' of x' we have $10w' \in W$. In combination with Proposition 4 this implies that $\overline{\mu}(1|x) \leq \frac{1}{2}$ for all x of type 0. Thus for such x and any $\mu \in M(T, x)$ we have $\mu(X_1) \leq \frac{1}{2}$, X_1 denoting the set of all sequences in X starting with the digit 1. Since $\delta_{1^\infty}(X_1) = 1$ this implies $\delta_{1^\infty} \notin M(T, x)$ for all x of type 0. □

Proof of $M_0(T) \neq \mathcal{M}(X, T)$. Since X has no isolated points, each of the points of type 1 (in the sense of Proposition 5), as a singleton, forms a nowhere dense subset. Since there are not more than countably many points of type 1, most points are of type 0. By Proposition 5 we have $\delta_{1^\infty} \notin M(T, x)$ for every x of type 0, hence $\delta_{1^\infty} \notin M_0(T)$. $\square$

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