The Hausdorff Measure of Regular ω-languages is Computable*

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Abstract

We show that there is an algorithm which computes Hausdorff dimension and Hausdorff measure of arbitrary regular ω-languages. Our algorithm is a generalization of the one given in [MS94] which was designed to compute Hausdorff dimension and Hausdorff measure of regular ω-languages closed in the Cantor topology.

Our new algorithm is based on a decomposition lemma for regular ω-languages and a relationship between the Hausdorff measure of regular ω-languages of a special shape and their closures.

In several previous papers we have shown how to calculate Hausdorff dimension and measure for certain classes of regular ω-languages (cf. [MS94], [St89], and [St93]). In this note we show that the results obtained in the papers [MS94] and [St93] can be used to give an effective procedure for the calculation of the Hausdorff measure for arbitrary regular ω-languages.

To this end we derive a decomposition lemma for regular ω-languages which extends in some sense decompositions presented by A. Arnold [Ar83], K. Wagner [Wa79] and L. Staiger and K. Wagner [SW74].

We assume the reader to be familiar with the basic facts of the theory of regular languages. Let X be a finite alphabet of cardinality $r := \operatorname{card} X \geq 2$, and let X^* and X^ω be the sets of (finite) words and ω-words over X, respectively. Concatenation is denoted by "$\cdot$" and the prefix relation by "$\sqsubseteq$". As usual, we consider X^ω as a topological space (Cantor space). The *closure* of a subset $F \subseteq X^\omega$, $\mathcal{C}(F)$, is described as $\mathcal{C}(F) := \{\xi : \mathbf{A}(\{\xi\}) \subseteq \mathbf{A}(F)\}$, where $\mathbf{A}(E)$ is the set of all finite prefixes of ω-words $\eta \in E$.

We postpone the definition of regularity for ω-languages to Section 2.

For more details on ω-languages and regular ω-languages see the survey papers [St97] and [Th90].

1 Hausdorff Dimension and Hausdorff Measure

First, we shall describe briefly the basic formulae needed for the definition of Hausdorff dimension and Hausdorff measure. For more background and motivation see Section 1 of [MS94].

We define, for $\alpha \in [0,\infty)$, $F \subseteq X^\omega$ and $V \subseteq X^*$,

$$\begin{array}{lcl} \mathbb{L}_\alpha(F;V) & := & \sum_{v\in V} r^{-\alpha\cdot|v|}, \text{ and} \\ \mathbb{L}_\alpha(F) & := & \liminf_{n\to\infty} \left\{ \mathbb{L}_\alpha(F;V) : V\cdot X^\omega \supseteq F \ \wedge\ \underline{\ell}(V) \geq n \right\}, \end{array} \tag{1}$$

where $\underline{\ell}(V) := \inf\{|v| : v \in V\}$.

Now consider $\mathbb{L}_\alpha(F)$ as a function of α. Then there is an $\alpha(F) \in [0,\infty)$ such that

$$\mathbb{L}_\alpha(F) = \begin{cases} \infty, & \text{if } \alpha < \alpha(F), \\ 0, & \text{if } \alpha > \alpha(F). \end{cases} \tag{2}$$

This number $\alpha(F)$ is called the *Hausdorff dimension* of F, $\dim F$, that is, the Hausdorff dimension of F is given by

$$\dim F = \sup\{\alpha : \alpha = 0 \vee \mathbb{L}_\alpha(F) = \infty\} = \inf\{\alpha : \mathbb{L}_\alpha(F) = 0\}.$$

The Hausdorff dimension for regular ω-languages has been proved to be computable (cf. [Ba89], [MW88] or [St89]). The aim of this note is to show how one can compute the value $\mathbb{L}_{\dim F}(F)$ (the Hausdorff measure of F) for an arbitrary regular ω-language.[1]

In [MS94] we presented an algorithm which computes, simultaneously, the dimension $\dim F$ and the value $\mathbb{L}_{\dim F}(F)$ for regular ω-languages closed[2] in the Cantor topology of X^ω. Our new algorithm will be based on this procedure. To this end we derive some properties of the function $\mathbb{L}_\alpha$. From the definition (1) one has immediately

$$\mathbb{L}_\alpha(w\cdot F) = r^{-\alpha\cdot|w|}\cdot \mathbb{L}_\alpha(F) \tag{3}$$

Since regular ω-languages are Borel sets in the Cantor space (cf. [St97], [Th90]), they are measurable with respect to $\mathbb{L}_\alpha$. Thus we have the following (cf. [Fa85]).

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[1] Observe that $\mathbb{L}_{\dim F}(F)$ is not specified by (2).

[2] A set $F \subseteq X^\omega$ is *closed* if $F = \mathcal{C}(F)$.

Proposition 1 *Assume $(F_i)_{i=0}^{\infty}$ is a family of mutually disjoint ω-languages measurable with respect to $I\!L_\alpha$. Then*

$$I\!L_\alpha(\bigcup_{i=0}^{\infty} F_i) = \sum_{i=0}^{\infty} I\!L_\alpha(F_i) \ .$$

Finally, we quote Theorem 6 of [MS94] (see also Lemma 4.5 of [St93]).

Proposition 2 *Let $V \subseteq X^*$ be regular and prefix-free. Then*

$$I\!L_\alpha\left(V^\omega\right) = I\!L_\alpha\left(\mathcal{C}(V^\omega)\right) \ .$$

2 Decomposition of Regular ω-languages

An ω-language $F \subseteq X^\omega$ is called *regular* provided there are a finite automaton $\mathfrak{A} = (X, S, s_0, \Delta)$ and a table $\mathcal{T} \subseteq \{S' : S' \subseteq S\}$ such that $\xi \in F$ if and only if $\mathit{Inf}(\mathfrak{A}, \xi) \in \mathcal{T}$ where $\mathit{Inf}(\mathfrak{A}, \xi)$ is the set of all states $s \in S$ through which the automaton $\mathfrak{A}$ runs infinitely often when reading the input ξ.
Observe that the ω-language $F = \{\xi : \mathit{Inf}(\mathfrak{A}, \xi) \in \mathcal{T}\}$ is the disjoint union of all sets $F_{S'} = \{\xi : \mathit{Inf}(\mathfrak{A}, \xi) = S'\}$ where $S' \in \mathcal{T}$.
We are going to split F into smaller mutually disjoint parts. Let $\mathfrak{A} = (X, S, s_0, \Delta)$ be fixed. We refer to a word $v \in X^*$ as (s, S')-*loop completing* if and only if

1. v is not the empty word,
2. $\Delta(s, v) = s$ and $\{\Delta(s, v') : v' \sqsubseteq v\} = S'$, and
3. $\{\Delta(s, v') : v' \sqsubseteq v''\} \subset S'$ for all proper prefixes $v'' \sqsubset v$ with $\Delta(s, v'') = s$,

and we call a word $w \in X^*$ (s, S')-*loop entering* provided

1. $\Delta(s_0, w) = s$, and
2. if $w = w' \cdot x$ for some $x \in X$ then $\Delta(s_0, w') \notin S'$.

Denote by $V_{(s,S')}$ the set of all (s,S')-loop completing words and by $W_{(s,S')}$ the set of all (s,S')-loop entering words. Both languages are regular and constructible from the finite automaton $\mathfrak{A} = (X, S, s_0, \Delta)$. Moreover, $V_{(s,S')}$ is prefix-free, whereas $W_{(s,S')}$ need not be so.

Nevertheless, every $\xi \in F_{S'}$ has a unique representation $\xi = w \cdot v_1 \cdots v_i \cdots$ where $w \in W_{(s,S')}$ and $v_i \in V_{(s,S')}$. Here the state $s \in S'$ is uniquely determined as the state succeeding the last state $\hat{s} \notin S'$ in the sequence $(\Delta(s_0, u))_{u \sqsubset \xi}$. Thus we obtain the following.

Lemma 3 (Decomposition Lemma) *Let $\mathfrak{A} = (X, S, s_0, \Delta)$ be a finite automaton and let $S' \subseteq S$. Then*

$$F_{S'} = \bigcup_{s \in S'} \bigcup_{w \in W_{(s,S')}} w \cdot V^{\omega}_{(s,S')} , \tag{4}$$

and the sets $w \cdot V^{\omega}_{(s,S')}$ are pairwise disjoint.

3 The Algorithm

Finally we derive the proof of our main result.

Theorem 4 *There is an algorithm which computes the Hausdorff measure $\mathbb{L}_{\dim F}(F)$ for every regular ω-language.*

From the decomposition in Lemma 3 we obtain via (3) and Proposition 1 a formula for the Hausdorff measure of $F_{S'}$:

$$\mathbb{L}_{\alpha}(F_{S'}) = \sum_{s \in S'} \Big(\sum_{w \in W_{(s,S')}} r^{-\alpha \cdot |w|} \Big) \cdot \mathbb{L}_{\alpha}(V^{\omega}_{(s,S')}) . \tag{5}$$

Since for regular languages $L \subseteq X^*$ the structure generating function of L, $\mathfrak{s}_L(t) := \sum_{w \in L} t^{|w|}$, is rational with integer coefficients and computable from L (cf. [KS86] or [SS78]), the sum $\sum_{w \in W_{(s,S')}} r^{-\alpha \cdot |w|}$ is computable, provided α is computable.

Proposition 2 shows that $\mathbb{L}_{\alpha}(V^{\omega}_{(s,S')}) = \mathbb{L}_{\alpha}(\mathcal{C}(V^{\omega}_{(s,S')}))$, because the language $V_{(s,S')}$ is regular and prefix-free.

Thus we obtain

$$\mathbb{L}_\alpha(F_{S'}) = \sum_{s\in S'} \mathfrak{s}_{W_{(s,S')}}(r^{-\alpha}) \cdot \mathbb{L}_\alpha(\mathcal{C}(V^\omega_{(s,S')})) \ . \tag{6}$$

Now the simultaneous computation of Hausdorff dimension and Hausdorff measure of a regular ω-language $F \subseteq X^\omega$ given by some finite automaton $\mathfrak{A} = (X, S, s_0, \Delta)$ and a table $\mathcal{T} \subseteq \{S' : S' \subseteq S\}$ proceeds as follows. Details should be carried out analogously to the algorithm described in Section 3 of [MS94].

1. For every $S' \in \mathcal{T}$ and every $s \in S'$ estimate the regular languages $V_{(s,S')}$ and $W_{(s,S')}$.
2. For every $S' \in \mathcal{T}$ estimate the adjacency matrix $\mathcal{A}_{S'}$ of $\mathcal{C}(V^\omega_{(s,S')})$.[3]
3. Calculate an eigenvalue $\lambda_{S'}$ of $\mathcal{A}_{S'}$ of maximum modulus.[4]
4. $\lambda_{\max} := \max\{|\lambda_{S'}| : S' \in \mathcal{T}\}$.
5. $\dim F := \log_r \lambda_{\max}$.
6. If $|\lambda_{S'}| < \lambda_{\max}$ then $\mathbb{L}_{\dim F}(\mathcal{C}(V^\omega_{(s,S')})) := 0$.
7. If $|\lambda_{S'}| = \lambda_{\max}$ then compute
   (a) $\mathbb{L}_{\dim F}(\mathcal{C}(V^\omega_{(s,S')}))$ according to Section 3 of [MS94], and
   (b) $\mathfrak{s}_{W_{(s,S')}}(\lambda^{-1}_{\max})$.
8. $$\mathbb{L}_{\dim F}(F) := \sum_{\lambda_{S'}=\lambda_{\max}} \sum_{s\in S'} \mathfrak{s}_{W_{(s,S')}}(\lambda^{-1}_{\max}) \cdot \mathbb{L}_{\dim F}(\mathcal{C}(V^\omega_{(s,S')})) \ .$$

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