

# On Kolmogorov Structure Functions

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## Abstract

All strings with low mutual information with the halting sequence will have flat Kolmogorov Structure Functions, in the context of Algorithmic Statistics. Assuming the Independence Postulate, strings with non-negligible information with the halting sequence are purely mathematical constructions, and cannot be found in the physical world.

## 1 Introduction

In statistics, one tries to determine a model (such as a parameter for a distribution) from data which is assumed to have noise. In the Minimum Description Principle [Gru07], the model that describes information with the shortest code is assumed to be the best model. The data is described as a two part code, where the first part is the model and the second part is the noise. In one of his last works, Kolmogorov suggested a two part code for individual strings  $x \in \{0, 1\}^*$  based off Kolmogorov Complexity. The first part (the model) is a set  $D$  containing  $x$ , the second part (the noise) is the code of  $x$  given  $D$ , of size  $\lceil \log |D| \rceil$ . Other works examined probabilities and also total computable functions as models [Vit02]. Kolmogorov suggested the following *structure function* at the Tallinn conference in Estonia, 1973.

$$\mathbf{H}_k(x) = \min\{\log |S| : x \in S, \mathbf{K}(S) \leq k\}.$$

The function  $\mathbf{K}$  is the prefix Kolmogorov complexity. This definition is used for the following function, which is a central definition of *Algorithmic Statistics* [VS15, VS17, VV04],

$$k \mapsto k + \mathbf{H}_k(x) - \mathbf{K}(x).$$

This function's equivalence to several other definitions is the main theorem of Algorithmic Statistics [SSV24]. Furthermore, Theorem 1 of [VS17] showed that any shape of the structure function is possible.

The structure function is flat for all strings with low mutual information with the halting sequence. Assuming the *Independence Postulate*, [Lev84, Lev13], strings with non-negligible mutual information with the halting sequence are exotic, in that they cannot be found in nature. Such strings are purely mathematical constructions.

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## 2 Bounds

We review the results of [GTV01], in particular Theorem of III.24, which I don't think is widely known.  $\mathbf{m}(x)$  is the algorithmic probability. The amount of information that the halting sequence  $\mathcal{H} \in \{0,1\}^\infty$  has about  $x \in \{0,1\}^*$  is  $\mathbf{I}(x; \mathcal{H}) = \mathbf{K}(x) - \mathbf{K}(x|\mathcal{H})$ . We use  $x <^+ y$ ,  $x >^+ y$  and  $x =^+ y$  to denote  $x < y + O(1)$ ,  $x + O(1) > y$  and  $x = y \pm O(1)$ , respectively. In addition,  $x <^{\log} y$  and  $x >^{\log} y$  denote  $x < y + O(\log y)$  and  $x + O(\log x) > y$ , respectively. For  $x, y \in \{0,1\}^*$ ,  $x \sqsubseteq y$  if  $y = xz$  for some  $z \in \{0,1\}^*$ .  $[A] = 1$  if mathematical statement  $A$  is true, and  $[A] = 0$  otherwise.

Let  $S_k = \{x : \mathbf{K}(x) \leq k\}$ . Let  $N_k = |S_k|$  where  $\log N_k =^+ k - \mathbf{K}(k)$ , due to [GTV01]. Let  $I_k^x$  be the index of  $x$  in an enumeration of  $S_k$ . For  $\mathbf{K}(x) = k$ , let  $m_x$  be the longest joint prefix of  $I_k^x$  and  $N_k$ . So  $m_x 0 \sqsubseteq I_k^x$  and  $m_x 1 \sqsubseteq N_k$ . Let  $S_x = \{y : m_x 0 \sqsubseteq I_k^y\}$ . So

$$\begin{aligned} \log |S_x| &=^+ k - \mathbf{K}(k) - \|m_x\| \\ \mathbf{K}(S_x) &<^+ \mathbf{K}(k) + \mathbf{K}(m_x) <^+ \mathbf{K}(k) + \|m_x\| + \mathbf{K}(\|m_x\|). \end{aligned}$$

**Theorem 1** ([GTV01]).

$$\|m_x\| < \mathbf{K}(\mathbf{K}(x)) + \mathbf{I}(x; \mathcal{H}) + O(\log \mathbf{I}(x; \mathcal{H})).$$

*Proof.* Let  $\nu(y) = c[\mathbf{K}(y) \leq k] \mathbf{m}(y) 2^{\|m_y\|} / (\|m_y\|^2)$ . For proper choice of  $c$ ,  $\nu$  is a semimeasure and computable relative to  $\mathcal{H}$  and  $k$ . So  $\mathbf{K}(x|\mathcal{H}, k) <^+ -\log \nu(x) =^+ \mathbf{K}(x) - \|m_x\| + 2 \log \|m_x\|$ .  $\square$

Note that with some additional effort, the  $\mathbf{K}(\mathbf{K}(x))$  term can be eliminated.

**Corollary 1.** For  $x \in \{0,1\}^*$ ,  $n = \mathbf{K}(x)$ , for all  $m \leq n$ ,  $m \in \mathbb{W}$ , there is a set  $S \ni x$  such that  $|S| = 2^m$  and  $\mathbf{K}(S) + m <^{\log} n + \mathbf{I}(x; \mathcal{H})$ .

**Claim 1.** Thus there exists a set  $S \ni x$  such that  $\mathbf{K}(S) <^{\log} 2\mathbf{K}(\mathbf{K}(x)) + \mathbf{I}(x; \mathcal{H})$  and  $\mathbf{K}(S) + \log |S| <^+ \mathbf{K}(x) + \mathbf{K}(\mathbf{K}(x)) + O(\log(\mathbf{I}(x; \mathcal{H}) + \mathbf{K}(\mathbf{K}(x))))$ . This fact combined with the following proposition characterizes the Kolmogorov Structure Function.

**Proposition 1.** Let  $S \ni x$ . For all  $s < \log |S|$  there exists a set  $S' \ni x$  such that  $|S'| \leq |S| 2^{-s}$  and  $\mathbf{K}(S') <^+ \mathbf{K}(S) + s + \mathbf{K}(s)$ .

### 3 Restricted Structure Functions

One potential method to create strings with non-simple Kolmogorov Structure Functions is to restrict the sets under consideration. Thus there is a set of sets  $\mathcal{S}$  such that

$$\mathbf{H}_k^{\mathcal{S}}(x) = \min\{\log |S| : x \in S \in \mathcal{S}, \mathbf{K}(S) \leq k\}.$$

This would banish the pesky set  $S_x$  defined in the last section. This was studied in Section 6 of [VS15]. However there is an inherent obstacle to proving such functions can have any shape. Proofs to statements (such as Theorem 10 in [VS15]) of such effect use a shape to (non-recursively) construct a string  $x$  whose structure function has that shape function  $R$  (up to a degree of precision depending on  $\mathcal{S}$ ). Thus  $\mathbf{K}(x|\mathcal{H}) <^+ \mathbf{K}(R)$ . Thus proofs saying that for every shape  $R$  there is a set  $x$  such that  $\mathbf{H}_k^{\mathcal{S}}(x)$  has shape  $R$  (up to a certain precision) also implies that  $\mathbf{I}(x; \mathcal{H}) >^+ \mathbf{K}(x) - \mathbf{K}(R)$ .

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