

# 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. We also discuss issues with set-restricted Kolmogorov Structure Functions.

## 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 Set-Restricted Structure Functions

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

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

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 function  $R$  to (non-recursively) construct a string  $x$  whose structure function has that shape  $R$  (up to a degree of precision depending on  $\mathcal{S}$ ). Thus the proof can be thought of as a program to produce  $x$  given  $R$  and  $\mathcal{H}$ , with  $\mathbf{K}(x|\mathcal{H}) <^+ \mathbf{K}(R)$ . 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  $\mathbf{I}(x; \mathcal{H}) >^+ \mathbf{K}(x) - \mathbf{K}(R)$ . In general, the Independence Postulate states if a string can be described by a small mathematical statement but has high Kolmogorov complexity then it cannot be found in the physical world. This presents an obstacle for constructive proofs in Algorithmic Information Theory.

### 4 Discussion

The Independence Postulate [Lev84, Lev13] states:

**IP:** *Let  $\alpha$  be a sequence defined with an  $n$ -bit mathematical statement (e.g., in PA or set theory), and a sequence  $\beta$  can be located in the physical world with a  $k$ -bit instruction set (e.g., ip-address). Then  $\mathbf{I}(\alpha : \beta) < k + n + c$  for some small absolute constant  $c$ .*

When I first learned of **IP**, I didn't realize how much of impact it could have on different fields of study. For example, **IP** and the Many Worlds Theory [Eve57] are in conflict because measuring the spin of a million electrons results in the creation of a world where a large prefix of Chaitin's Omega,  $\Omega$ , is found at a small address. Furthermore, **IP** causes issues in Constructor Theory [Deu13], which characterizes tasks in physics as either possible or impossible. This raises the question: "Is it possible or impossible to find large prefixes of  $\Omega$ ?" The answer causes trouble for either Constructor Theory or **IP**.

This note reiterates that **IP** implies Algorithmic Statistics does not study strings in the physical world. The intention is not to denigrate the theory; a majority of my work (including [Eps23c, Eps23b, Eps24, Eps23a]) is descendent from Algorithmic Statistics. My interpretation of the Kolmogorov Structure Function is that it provides a means to know that a string  $x$  has high  $\mathbf{I}(x; \mathcal{H})$ .

## References

- [Deu13] D. Deutsch. Constructor theory. *Synthese*, 190(18):4331–4359, 2013.
- [Eps23a] S. Epstein. The EL Theorem, 2023.
- [Eps23b] Samuel Epstein. Kolmogorov Derandomization. 2023. HAL Archive, hal-04292439, <https://hal.science/hal-04292439>.
- [Eps23c] Samuel Epstein. On Outliers. 2023. HAL Archive, hal-04285958, <https://hal.science/hal-04285958>.
- [Eps24] S. Epstein. On Exotic Sequences. <http://www.jptheorygroup.org/doc/OnExoticSequences.pdf>, 2024.
- [Eve57] Hugh Everett. "relative state" formulation of quantum mechanics. *Rev. Mod. Phys.*, 29, 1957.
- [Gru07] P. Grunwald. *The Minimum Description Length Principle*. The MIT Press, 2007.
- [GTV01] P. Gács, J. Tromp, and P. Vitányi. Algorithmic statistics. *Information Theory, IEEE Transactions on*, 47:2443 – 2463, 2001.
- [Lev84] L. A. Levin. Randomness conservation inequalities; information and independence in mathematical theories. *Information and Control*, 61(1):15–37, 1984.
- [Lev13] L. A. Levin. Forbidden information. *J. ACM*, 60(2), 2013.
- [SSV24] A. Semenov, A. Shen, and N. Vereshchagin. Kolmogorov’s Last Discovery? (Kolmogorov and Algorithmic Statistics). *Theory of Probability & Its Applications*, 68(4):582–606, 2024.
- [Vit02] P. Vitányi. Meaningful information. In *Algorithms and Computation*, pages 588–599, Berlin, Heidelberg, 2002. Springer Berlin Heidelberg.
- [VS15] N. Vereshchagin and A. Shen. *Algorithmic Statistics Revisited*, pages 235–252. Springer International Publishing, 2015.
- [VS17] N. Vereshchagin and A. Shen. *Algorithmic Statistics: Forty Years Later*, pages 669–737. Springer International Publishing, 2017.
- [VV04] N. Vereshchagin and P. Vitányi. Kolmogorov’s structure functions and model selection. *IEEE Transactions on Information Theory*, 50(12):3265–3290, 2004.