

Outliers in Dynamics

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Abstract

We show that outliers occur almost surely in computable dynamics over infinite sequences. Ever greater outliers can be found as the number of visited states increase.

1 Introduction

An outlier is an observation whose value lies outside the set of values considered likely according to some hypothesis (usually one based on other observations); an isolated point. In the realm of algorithmic information theory, outliers are modeled using the deficiency of randomness. The randomness deficiency of an infinite sequence $\alpha \in \Sigma^\infty$ with respect to a computable probability measure P is $\mathbf{D}(\alpha|P) = \sup_n -\log P(\alpha[0..n]) - \mathbf{K}(\alpha[0..n])$. The term \mathbf{K} is the prefix free Kolmogorov complexity.

The definition of a randomness deficiency is a very useful mathematical construct, and can be used to show the ubiquity of outliers in different constructs. A sampling method is a probabilistic program that when given n , outputs with probability 1, n unique elements, either numbers or infinite sequences. In [Eps21], it was proven that sampling methods produce outliers. In [Eps22], it was proven that for ergodic dynamical systems, ever greater outlying states occur with diminishing measure. In this paper, we show that arbitrary (potentially non-ergodic) computable dynamical systems over Σ^∞ produce outliers, where as more states are visited, more and greater outliers are guaranteed to occur.

A computable dynamical system (λ, δ) , over Σ^∞ consists of a computable starting state probability λ over Σ^∞ and a computable transition function $\delta : \Sigma^\infty \rightarrow \Sigma^\infty$. We assume that the dynamical system is non-degenerate, in that for λ -a.e. starting states α , an infinite number of states is visited using δ .

Theorem. *There is a $d \in \mathbb{N}$, where for computable probability μ over Σ^∞ and computable dynamics (λ, δ) over Σ^∞ , for λ -a.e. starting states $\alpha \in \Sigma^\infty$, there exists $c_\alpha \in \mathbb{N}$, where among the first 2^m states visited, for any $n < m$, there are at least 2^n states β with $\mathbf{D}(\beta|\mu) > m - n - d \log m - c_\alpha$. Furthermore, for the smallest such c_α , $\mathbf{E}_{\alpha \sim \lambda} [c_\alpha - O(\log c_\alpha)] < O(\mathbf{K}(\lambda, \delta, \mu))$.*

The proof technique is two stages. First is to prove that certain finite sets of natural numbers or infinite sequences have high mutual information, \mathbf{I} , with the halting sequence. This is represented in Theorems 1 and 2. The second step is to use conservation properties of \mathbf{I} , shown in Theorem 3, to achieve the main theorem of the paper. It remains to be seen whether there is a more direct method to proving the results.

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2 Conventions

We use \mathbb{N} , \mathbb{Q} , \mathbb{R} , Σ , Σ^* , and Σ^∞ to represent natural numbers, rational numbers, reals, bits, finite strings, and infinite strings. The removal of the last bit of a string is denoted by $(p0^-)=(p1^-)=p$, for $p \in \Sigma^*$. We use $\Sigma^{*\infty}$ to denote $\Sigma^* \cup \Sigma^\infty$, the set of finite and infinite strings. For $x \in \Sigma^{*\infty}$, $y \in \Sigma^{*\infty}$, we say $x \sqsubseteq y$ if $x = y$ or $x \in \Sigma^*$ and $y = xz$ for some $z \in \Sigma^{*\infty}$. Also $x \sqsubset y$ if $x \sqsubseteq y$ and $x \neq y$. The indicator function of a mathematical statement A is denoted by $[A]$, where if A is true then $[A] = 1$, otherwise $[A] = 0$. For sets Z of infinite strings, $Z_n = \{\alpha[0..n] : \alpha \in Z\}$ and $\langle Z \rangle = \langle Z_1 \rangle \langle Z_2 \rangle \langle Z_3 \rangle \dots$.

As is typical of the field of algorithmic information theory, the theorems in this paper are relative to a fixed universal machine, and therefore their statements are only relative up to additive and logarithmic precision. For positive real functions f the terms $<^+ f$, $>^+ f$, $=^+ f$ represent $< f + O(1)$, $> f - O(1)$, and $= f \pm O(1)$, respectively. In addition $<^* f$, $>^* f$ denote $< f/O(1)$, $> f/O(1)$. The terms $=^* f$ denotes $<^* f$ and $>^* f$. For nonnegative real function f , the terms $<^{\log} f$, $>^{\log} f$, $=^{\log} f$ represent the terms $< f + O(\log(f+1))$, $> f - O(\log(f+1))$, and $= f \pm O(\log(f+1))$, respectively. A discrete measure is a nonnegative function $Q : \mathbb{N} \rightarrow \mathbb{R}_{\geq 0}$ over natural numbers. The support of a measure Q is the set of all elements whose Q value is positive, with $\text{Supp}(Q) = \{a : Q(a) > 0\}$. A measure is elementary if its support is finite and its range is a subset of \mathbb{Q} . We say that Q is a probability measure if $\sum_a Q(a) = 1$.

$T_y(x)$ is the output of algorithm T (or \perp if it does not halt) on input $x \in \Sigma^*$ and auxiliary input $y \in \Sigma^{*\infty}$. T is prefix-free if for all $x, s \in \Sigma^*$ with $s \neq \emptyset$, and $y \in \Sigma^{*\infty}$, either $T_y(x) = \perp$ or $T_y(xs) = \perp$. The complexity of $x \in \Sigma^*$ with respect to T_y is $\mathbf{K}_T(x|y) = \min\{\|p\| : T_y(p) = x\}$.

There exists optimal for \mathbf{K} prefix-free algorithm U , meaning that for all prefix-free algorithms T , there exists $c_T \in \mathbb{N}$, where $\mathbf{K}_U(x|y) \leq \mathbf{K}_T(x|y) + c_T$ for all $x \in \Sigma^*$ and $y \in \Sigma^{*\infty}$. For example, one can take a universal prefix-free algorithm U , where for each prefix-free algorithm T , there exists $t \in \Sigma^*$, with $U_y(tx) = T_y(x)$ for all $x \in \Sigma^*$ and $y \in \Sigma^{*\infty}$. The function $\mathbf{K}(x|y)$, defined to be $\mathbf{K}_U(x|y)$, is the Kolmogorov complexity of $x \in \Sigma^*$ relative to $y \in \Sigma^{*\infty}$. When we say that a universal Turing machine is relativized to an object, this means that an encoding of the object is provided to the universal Turing machine on an auxiliary tape.

The chain rule for Kolmogorov complexity is $\mathbf{K}(x, y) =^+ \mathbf{K}(x) + \mathbf{K}(y|\langle x, \mathbf{K}(x) \rangle)$. The mutual information in finite strings x and y relative to $z \in \Sigma^*$ is $\mathbf{I}(x : y | z) = \mathbf{K}(x|z) + \mathbf{K}(y|z) - \mathbf{K}(\langle x, y \rangle | z) =^+ \mathbf{K}(x|z) - \mathbf{K}(x|\langle y, \mathbf{K}(y|z), z \rangle)$. The universal probability of a number $a \in \mathbb{N}$ is $\mathbf{m}(a|y) = \sum_z [U_y(z) = a] 2^{-\|z\|}$. The coding theorem states $-\log \mathbf{m}(a|y) =^+ \mathbf{K}(a|y)$.

For computable probability measure λ over Σ^∞ , $\mathbf{K}(\lambda)$ is the size of the shortest program that can compute $\lambda(x \Sigma^\infty)$, for all $x \in \Sigma^*$. For computable function $\delta : \Sigma^\infty \rightarrow \Sigma^\infty$, $\mathbf{K}(\delta)$ is the size of the shortest program on the input tape that outputs $\delta(\alpha)$ when α is on the auxiliary tape. The halting sequence $\mathcal{H} \in \Sigma^\infty$ is the infinite string where $\mathcal{H}[i] = [U(i) \neq \perp]$ for all $i \in \mathbb{N}$. The amount of information that $a \in \mathbb{N}$ has with \mathcal{H} is denoted by $\mathbf{I}(a : \mathcal{H}) = \mathbf{K}(a) - \mathbf{K}(a|\mathcal{H})$.

The deficiency of randomness of x with respect to elementary measure Q and $v \in \mathbb{N}$ is $\mathbf{d}(x|Q, v) = \lfloor -\log Q(x) \rfloor - \mathbf{K}(x|\langle Q \rangle, v)$. The stochasticity of $a \in \mathbb{N}$, conditional to $b \in \mathbb{N}$, is measured by $\mathbf{Ks}(a|b) = \min\{\mathbf{K}(Q|b) + 3 \log \max\{\mathbf{d}(a|Q, b), 1\} : Q \text{ is an elementary probability measure}\}$. We have $\mathbf{Ks}(a) = \mathbf{Ks}(a|\emptyset)$, with $\mathbf{Ks}(a|b) <^+ \mathbf{Ks}(a) + \mathbf{K}(b)$.

3 Sets of Numbers

Theorem 1 *Relativized to computable probability p over \mathbb{N} , for $D \subset \Sigma^*$, $|D| = 2^s$, $m \in [0, s-1]$, there are 2^m elements $a \in D$, with $s - m < \mathbf{d}(a|p) + \mathbf{Ks}(D) + O(\log s)$.*

Proof. We relativize the universal Turing machine U to s for the duration of the proof, which can be done as the theorem has precision $O(\log s)$. Let Q be an elementary probability distribution that realizes $\mathbf{Ks}(D)$. Let $d = \mathbf{d}(D|Q)$ be the deficiency of randomness of D with respect to Q . Let V be the combined elements of encoded sets of size 2^s in the support of Q . We create an algorithm, that given Q and s produces 2^{s-1} sets $F_i \subseteq V$. We start with the first round. Suppose each element of V is selected independently with probability $cd2^{-s}$, where c is a constant to be chosen later. The selected set is F_1 , and $\mathbf{E}[p(F_1)] \leq cd2^{-s}$. Furthermore

$$\mathbf{E}[Q(\{G : |G| = 2^s, G \cap F_1 = \emptyset\})] \leq \sum_G Q(G)(1 - cd2^{-s})^{2^s} < e^{-cd}.$$

Thus a finite set F_1 can be chosen such that $p(F_1) \leq 2cd2^{-s}$ and $Q(\{G : |G| = 2^s, G \cap F_1 = \emptyset\}) \leq e^{1-cd}$.

Now it must be that $D \cap F_1 \neq \emptyset$. Otherwise, using the Q -test, $t(G) = [|G| = 2^s, G \cap F_1 = \emptyset]e^{cd-1}$, we have

$$\begin{aligned} \mathbf{K}(D|Q, d, c) &<^+ -\log Q(D) - (\log e)cd \\ (\log e)cd &<^+ -\log Q(D) - \mathbf{K}(D|Q) + \mathbf{K}(d, c) \\ (\log e)cd &<^+ d + \mathbf{K}(d, c), \end{aligned}$$

which is a contradiction for large enough c solely dependent on the universal Turing machine U . Thus there is an $a \in D \cap F_1$, where

$$\begin{aligned} \mathbf{K}(a) &<^+ -\log p(a) + \log d - s + \mathbf{K}(d) + \mathbf{K}(Q) \\ s &<^+ \mathbf{d}(a|P) + \mathbf{Ks}(D). \end{aligned}$$

We define the construction of set F_i given that the first $i-1$ rounds have already occurred. Let $F_{<i} = \bigcup_{j=1}^{i-1} F_j$. A set G is eligible if $|G| = 2^s$, and $|G \setminus F_{<i}| \geq 2^s - (i-1)$. Set F_i is selected at random from V , with each element selected at random with probability cd_i2^{-s} , with $d_i = d \log i$. $\mathbf{E}[p(F_i)] \leq cd_i2^{-s}$.

$$\begin{aligned} &\mathbf{E}[Q(\{G : G \text{ is eligible}, (G \setminus F_{<i}) \cap F_i = \emptyset\})] \\ &\leq \sum_{\text{eligible } G} Q(G)(1 - cd_i2^{-s})^{2^s - (i-1)} \\ &\leq e^{-cd_i2^{-s}(2^s - (i-1))} \leq e^{-cd_i/2}. \end{aligned}$$

Thus a finite set F_i can be chosen such that $p(F_i) \leq 2cd_i2^{-s}$ and $Q(\{G : G \text{ is eligible}, (G \setminus F_{<i}) \cap F_i = \emptyset\}) \leq e^{-cd_i/2+1}$. It must be that on the rounds i that D is eligible, $(D \setminus F_{<i}) \cap F_i \neq \emptyset$. Otherwise one can create a Q -test $t_i(G) = [G \text{ is eligible}, (G \setminus F_{<i}) \cap F_i = \emptyset]e^{cd_i/2-1}$. Thus $t_i(D) \neq 0$ and

$$\begin{aligned} \mathbf{K}(D|Q, d_i, i, c) &<^+ -\log Q(D) - (\log e)cd_i/2 \\ .5(\log e)cd \log i &<^+ -\log Q(D) - \mathbf{K}(D|Q) + \mathbf{K}(d_i, i, c) \\ .5(\log e)cd \log i &<^+ d + \mathbf{K}(d, \mathbf{K}(i), i, c). \end{aligned}$$

This is a contradiction for large enough c dependent solely on the universal Turing machine U . Thus on rounds i where D is eligible, there exist an $a \in (D \setminus F_{<i}) \cap F_i$, with

$$\begin{aligned} \mathbf{K}(a) &<^+ -\log p(a) + \log d_i - s + \mathbf{K}(d_i) + \mathbf{K}(i) + \mathbf{K}(Q) \\ s &< \mathbf{d}(a|p) + \log i + O(\log \log i) + \log d + \mathbf{K}(d) + \mathbf{K}(Q) \\ s - \log i &< \mathbf{d}(a|p) + \mathbf{Ks}(D) + O(\log s). \end{aligned} \tag{1}$$

On rounds i in which D is not eligible, then there exist rounds $j < i$ where $|(D \setminus F_{<j}) \cap F_j| > 1$. And for each such element in the intersection, a bound on their deficiency of randomness similar to Equation 1 can be proven. \square

4 Left-Total Machines

We say $x \in \Sigma^*$ is total with respect to a machine if the machine halts on all sufficiently long extensions of x . More formally, x is total with respect to T_y for some $y \in \Sigma^{*\infty}$ if there exists a finite prefix free set of strings $Z \subset \Sigma^*$ where $\sum_{z \in Z} 2^{-\|z\|} = 1$ and $T_y(xz) \neq \perp$ for all $z \in Z$. We say $\alpha \in \Sigma^{*\infty}$ is to the “left” of $\beta \in \Sigma^{*\infty}$, and use the notation $\alpha \triangleleft \beta$, if there exists $x \in \Sigma^*$ such that $x0 \sqsubseteq \alpha$ and $x1 \sqsubseteq \beta$. A machine T is left-total if for all auxiliary strings $\alpha \in \Sigma^{*\infty}$ and for all $x, y \in \Sigma^*$ with $x \triangleleft y$, one has that $T_\alpha(y) \neq \perp$ implies that x is total with respect to T_α . An example left-total machine can be seen in Figure 1.

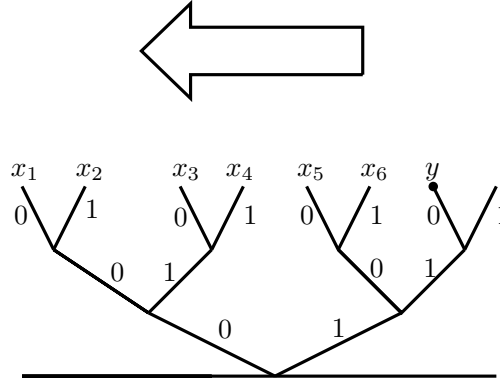


Figure 1: The above diagram represents the domain of a left total machine T with the 0 bits branching to the left and the 1 bits branching to the right. For $i \in \{1, \dots, 5\}$, $x_i \triangleleft x_{i+1}$ and $x_i \triangleleft y$. Assuming $T(y)$ halts, each x_i is total. This also implies each x_i^- is total as well.

For the remaining part of this paper, we can and will change the universal self delimiting machine U into an optimal left-total machine U' . For a detailed explanation on how to construct a left-total universal Turing machine, we refer readers to [Eps21].

Without loss of generality, the complexity terms of this paper are defined with respect to the optimal left total machine U . The infinite border sequence $\mathcal{B} \in \Sigma^\infty$ represents the unique infinite sequence such that all its finite prefixes have total and non total extensions. The term “border” is used because for any string $x \in \Sigma^*$, $x \triangleleft \mathcal{B}$ implies that x total with respect to U and $\mathcal{B} \triangleleft x$ implies that U will never halt when given x as an initial input. Figure 2 shows the domain of U with respect to \mathcal{B} .

Using Lemma 1, relativized to b ,

$$\begin{aligned}\mathbf{K}(x|b) &< -\log p(x) - s + m + \mathbf{I}(D : \mathcal{H}|b) + O(\log s + \log \mathbf{I}(D : \mathcal{H}|b)) \\ s - m &< \log(\mathbf{m}(x)/p(x)) + \mathbf{K}(b) + \mathbf{I}(D : \mathcal{H}|b) + O(\log s + \log(\mathbf{I}(D : \mathcal{H}|b) + \mathbf{K}(b))).\end{aligned}$$

By Lemma 2,

$$s - m < \log(\mathbf{m}(x)/p(x)) + \mathbf{I}(D : \mathcal{H}) + \mathbf{K}(b|D, \|b\|) + O(\log s + \log(\mathbf{I}(D : \mathcal{H}) + \mathbf{K}(b|D, \|b\|))).$$

Since $D \subseteq \Sigma^{\mathbf{bb}(b)}$, $\mathbf{K}(b|D, \|b\|) = O(1)$, as a program can output the leftmost total string y of length $\|b\|$ such that $\mathbf{bb}(y)$ is the length of the strings in D . So

$$s - m < \log(\mathbf{m}(x)/p(x)) + \mathbf{I}(D : \mathcal{H}) + O(\log s + \log \mathbf{I}(D : \mathcal{H})).$$

We have that $\mathbf{K}(D|\langle Z \rangle) <^+ \mathbf{K}(\|b\|) + \mathbf{K}(s)$, as D is computable from $\langle Z \rangle$, $\|b\|$, and s . This is because b is computable from its length, s , and $\langle Z \rangle$, and thus so is $D = Z_{\mathbf{bb}(b)}$. By the Definition 1 of the mutual information between infinite sequences,

$$\begin{aligned}\mathbf{I}(D : \mathcal{H}) &<^+ \mathbf{I}(\langle Z \rangle : \mathcal{H}) + \mathbf{K}(D|\langle Z \rangle) \\ &<^+ \mathbf{I}(\langle Z \rangle : \mathcal{H}) + \mathbf{K}(\|b\|) + \mathbf{K}(s) \\ &<^+ \mathbf{I}(\langle Z \rangle : \mathcal{H}) + 2 \log \mathbf{I}(D : \mathcal{H}) + \mathbf{K}(s) \\ &<^{\log} \mathbf{I}(\langle Z \rangle : \mathcal{H}) + \mathbf{K}(s),\end{aligned}\tag{2}$$

where Equation 2 is due to Lemma 3, noting $\mathbf{K}(b|D, \|b\|) = O(1)$. So there is an $\alpha \in Z$, $x \sqsubset \alpha$, with

$$\begin{aligned}s - m &< \log(\mathbf{m}(x)/p(x)) + \mathbf{I}(D : \mathcal{H}) + O(\log s + \log \mathbf{I}(D : \mathcal{H})) \\ s - m &< \mathbf{D}(\alpha|P) + \mathbf{I}(\langle Z \rangle : \mathcal{H}) + O(\log s + \mathbf{I}(\langle Z \rangle : \mathcal{H})).\end{aligned}$$

6 Outliers in Dynamics

Theorem 3 ([Ver21, Lev74, Gei12])

- $\Pr_\lambda(\mathbf{I}(\alpha : \mathcal{H}) > n) \stackrel{*}{<} 2^{-n+\mathbf{K}(\lambda)}.$
- $\mathbf{I}(f(\alpha) : \mathcal{H}) <^+ \mathbf{I}(\alpha : \mathcal{H}) + \mathbf{K}(f).$
- $\mathbf{E}_\lambda [2^{\mathbf{I}(\alpha : \mathcal{H})}] \stackrel{*}{<} 2^{\mathbf{K}(\lambda)}.$

Theorem 4 *There is a $d \in \mathbb{N}$, where for computable probability μ over Σ^∞ and computable dynamics (λ, δ) over Σ^∞ , for λ -a.e. starting states $\alpha \in \Sigma^\infty$, there exists $c_\alpha \in \mathbb{N}$, where among the first 2^m states visited, for any $n < m$, there are at least 2^n states β with $\mathbf{D}(\beta|\mu) > m - n - d \log m - c_\alpha$. Furthermore, for the smallest such c_α , $\mathbf{E}_{\alpha \sim \lambda} [c_\alpha - O(\log c_\alpha)] < O(\mathbf{K}(\lambda, \delta, \mu))$.*

Proof. Fix a starting state $\alpha \in \Sigma^\infty$ and fix $d \in \mathbb{N}$. Assume α has property A , in which for all $c_\alpha \in \mathbb{N}$, there exists $m, n \in \mathbb{N}$, $m < n$, where the first 2^n states $Z \subset \Sigma^\infty$ visited has less than 2^m states $\beta \in Z$, with

$$\mathbf{D}(\beta|\mu) > n - m - d \log n - c_\alpha.$$

Therefore, due to Theorem 2 there exists a state $\beta \in Z$, with

$$\mathbf{D}(\beta|\mu) \leq n - m - d \log n - c_\alpha$$

and

$$n - m < \mathbf{D}(\beta|\mu) + \mathbf{I}(Z : \mathcal{H}) + O(\mathbf{K}(\mu) + \log n + \log \mathbf{I}(Z : \mathcal{H})).$$

Due to Theorem 3, we have

$$\mathbf{I}(Z : \mathcal{H}) <^+ \mathbf{I}(\alpha : \mathcal{H}) + \mathbf{K}(n) + \mathbf{K}(\delta),$$

so

$$n - m < \mathbf{D}(\beta|\mu) + \mathbf{I}(\alpha : \mathcal{H}) + \mathbf{K}(\delta) + O(\mathbf{K}(\mu) + \log n + \log(\mathbf{I}(\alpha : \mathcal{H}) + \mathbf{K}(\delta))).$$

So

$$n - m < n - m - d \log n - c_\alpha + \mathbf{I}(\alpha : \mathcal{H}) + \mathbf{K}(\delta) + O(\log n + \log(\mathbf{I}(\alpha : \mathcal{H}) + \mathbf{K}(\delta))),$$

implying

$$d \log n + c_\alpha < \mathbf{I}(\alpha : \mathcal{H}) + \mathbf{K}(\delta) + O(\mathbf{K}(\mu) + \log n + \log(\mathbf{I}(\alpha : \mathcal{H}) + \mathbf{K}(\delta))).$$

Thus for large enough d , dependent solely on the universal Turing machine U , $\mathbf{I}(\alpha : \mathcal{H}) = \infty$. Thus by Theorem 3, λ -a.e. states α do not have the property A .

By the reasoning above, the smallest such c_α has $c_\alpha <^{\log} \mathbf{I}(\alpha : \mathcal{H}) + \mathbf{K}(\delta) + O(\mathbf{K}(\mu))$. So $c_\alpha - O(\log c_\alpha) < \mathbf{I}(\alpha : \mathcal{H}) + \mathbf{K}(\delta) + O(\mathbf{K}(\mu))$. So $\mathbf{E}_{\alpha \sim \lambda} [2^{c_\alpha} c_\alpha^{-O(1)}] < \mathbf{E}_{\alpha \sim \lambda} [2^{\mathbf{I}(\alpha : \mathcal{H}) + \mathbf{K}(\delta) + O(\mathbf{K}(\mu))}]$ implies $\mathbf{E}_{\alpha \sim \lambda} [c_\alpha - O(\log c_\alpha)] < \mathbf{K}(\lambda) + \mathbf{K}(\delta) + O(\mathbf{K}(\mu)) < O(\mathbf{K}(\lambda, \delta, \mu))$. \square

7 Discussion

The paper proves results for discrete time dynamical systems. An open problem is how outliers manifest in continuous time dynamical systems. Another avenue of research involves the connections of outliers in dynamical systems to thermodynamics. A good starting point for research into this area would be the paper [Gac94].

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