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# An impossibility result for process discrimination.

Daniil Ryabko

## Abstract

Two series of binary observations  $x_1, x_2, \dots$  and  $y_1, y_2, \dots$  are presented: at each time  $n \in \mathbb{N}$  we are given  $x_n$  and  $y_n$ . It is assumed that the sequences are generated independently of each other by two stochastic processes. We are interested in the question of whether the sequences represent a typical realization of two different processes or of the same one. We demonstrate that this is impossible to decide in the case when the processes are  $B$ -processes. It follows that discrimination is impossible for the set of all (finite-valued) stationary ergodic processes in general. This result means that every discrimination procedure is bound to err with non-negligible frequency when presented with sequences from some of such processes. It contrasts earlier positive results on  $B$ -processes, in particular those showing that there are consistent  $\bar{d}$ -distance estimates for this class of processes.

*Keywords: Process discrimination, B-processes, stationary ergodic processes, time series, homogeneity testing*

## 1 Introduction

Given two series of observations we wish to decide whether they were generated by the same process or by different ones. The question is relatively simple when the time series are generated by a source of independent identically distributed outcomes. It is far less clear how to solve the problem for more general cases, such as the case of stationary ergodic time series. In this work we demonstrate that the question is impossible to decide even in the weakest asymptotic sense, for a wide class of processes, which is a subset of the set of all stationary ergodic processes.

More formally, two series of binary observations  $x_1, x_2, \dots$  and  $y_1, y_2, \dots$  are presented sequentially. A *discrimination procedure*  $D$  is a family of mappings  $D_n : X^n \times X^n \rightarrow \{0, 1\}$ ,  $n \in \mathbb{N}$ , that maps a pair of samples  $(x_1, \dots, x_n)$ ,  $(y_1, \dots, y_n)$  into a binary (“yes” or “no”) answer: the samples are generated by different distributions, or they are generated by the same distribution.

A discrimination procedure  $D$  is *asymptotically correct for a set  $\mathcal{C}$  of process distributions* if for any two distributions  $\rho_x, \rho_y \in \mathcal{C}$  independently generating the sequences  $x_1, x_2, \dots$  and  $y_1, y_2, \dots$  correspondingly the expected output converges to the correct answer: the following limit exists and the equality holds

$$\lim_{n \rightarrow \infty} \mathbf{E}D_n((x_1, \dots, x_n), (y_1, \dots, y_n)) = \begin{cases} 0 & \text{if } \rho_x = \rho_y \\ 1 & \text{otherwise} \end{cases} .$$

Note that one can consider other notions of asymptotic correctness, for example one can require the output to stabilize on the correct answer with probability 1. The notion of correctness that we consider is perhaps one of the weakest. Clearly, asymptotically correct discriminating procedures exist for many classes of processes, for example for the class of all i.i.d. processes, or various parametric families, see e.g. [2, 5]; some related positive results on hypothesis testing for stationary ergodic process can be found in [12, 13].

We will show that asymptotically correct discrimination procedures do not exist for the class of  $B$ -processes, or for the class of all stationary ergodic processes. This result for  $B$ -processes is interesting in view of some previously established results; thus, in [10, 9] it is shown that consistent estimates of  $\bar{d}$ -distance for  $B$ -processes (see definitions below) exist, while it is impossible to estimate this distance outside this class (i.e. in general for stationary ergodic processes). So, our result demonstrates that discrimination is harder than distance estimation. The distinction between these problems becomes very apparent in view of the positive results of [13], which show that consistent change point estimates and process classification

procedures exist for the class of stationary ergodic processes. The result of the present work also complements earlier negative results on  $B$ -processes, such as [14] that shows that upper and lower divergence rates need not be the same for  $B$ -processes, and on stationary ergodic processes, such as [11, 3, 1, 6], that establish negative results concerning prediction, density estimation, and testing properties of processes. It is worth noting that  $B$ -processes are of particular importance for information theory, in particular, since they are what can be obtained by stationary codings of memoryless processes [7, 15].

Next we briefly introduce the notation. We are considering stationary ergodic processes (time series), defined as probability distributions on the set of one-way infinite sequences  $A^\infty$ , where  $A = \{0, 1\}$ . We will also consider stationary ergodic Markov chains on a countable set of states; for now let the set of states be  $\mathbb{N}$ . Any function  $f : \mathbb{N} \rightarrow A$  mapping the set of states to  $A$ , together with a stationary ergodic Markov chain  $m$  defines a stationary ergodic binary-valued process, whose value on each time step is the value of  $f$  applied to the current state of  $m$ .

For two finite-valued stationary processes  $\rho_x$  and  $\rho_y$  the  $\bar{d}$ -distance  $\bar{d}(\rho_x, \rho_y)$  is said to be less than  $\varepsilon$  if there exists a single stationary process  $\nu_{xy}$  on pairs  $(x_n, y_n)$ ,  $n \in \mathbb{N}$ , such that  $x_n$ ,  $n \in \mathbb{N}$  are distributed according to  $\rho_x$  and  $y_n$  are distributed according to  $\rho_y$  while

$$\nu_{xy}(x_1 \neq y_1) \leq \varepsilon. \quad (1)$$

The infimum of the  $\varepsilon$ 's for which a coupling can be found such that (1) is satisfied is taken to be the  $\bar{d}$ -distance between  $\rho_x$  and  $\rho_y$ . A process is called a  $B$ -process (or a Bernoulli process) if it is in the  $\bar{d}$ -closure of the set of all aperiodic stationary ergodic  $k$ -step Markov processes, where  $k \in \mathbb{N}$ . For more information on  $\bar{d}$ -distance and  $B$ -processes the reader is referred to [10, 8].

## 2 Main results

The main result of this work is the following theorem; the construction used in the proof is based on the same ideas as the construction used in [11] (see also [3]) to demonstrate that consistent prediction for stationary ergodic processes is impossible.

**Theorem 1** *There is no asymptotically correct discrimination procedure for the class of  $B$ -processes.*

Since the class of  $B$ -processes is a subset of the class of all stationary ergodic processes, the following corollary holds true.

**Corollary 1** *There is no asymptotically correct discrimination procedure for the class of stationary ergodic processes.*

*Proof of Theorem 1:* We will assume that asymptotically correct discrimination procedure  $D$  for the class of all  $B$ -processes exists, and will construct a  $B$ -process  $\rho$  such that if both sequences  $x_i$  and  $y_i$ ,  $i \in \mathbb{N}$  are generated by  $\rho$  then  $\mathbf{E}D_n$  diverges; this contradiction will prove the theorem.

The scheme of the proof is as follows. On Step 1 we construct a sequence of processes  $\rho_{2k}$ ,  $\rho_{d2k+1}$ , and  $\rho_{u2k+1}$ , where  $k = 0, 1, \dots$ . On Step 2 we construct a process  $\rho$ , which is shown to be the limit of the sequence  $\rho_{2k}$ ,  $k \in \mathbb{N}$ , in  $\bar{d}$ -distance. On Step 3 we show that two independent runs of the process  $\rho$  have a property that (with high probability) they first behave like two runs of a single process  $\rho_0$ , then like two runs of two different processes  $\rho_{u1}$  and  $\rho_{d1}$ , then like two runs of a single process  $\rho_2$ , and so on, thereby showing that the test  $D$  diverges and obtaining the desired contradiction.

Assume that there exists an asymptotically correct discriminating procedure  $D$ . Fix some  $\varepsilon \in (0, 1/2)$  and  $\delta \in [1/2, 1)$ , to be defined on Step 3.

*Step 1.* We will construct the sequence of process  $\rho_{2k}$ ,  $\rho_{u2k+1}$ , and  $\rho_{d2k+1}$ , where  $k = 0, 1, \dots$

*Step 1.0.* Construct the process  $\rho_0$  as follows. A Markov chain  $m_0$  is defined on the set  $\mathbb{N}$  of states. From each state  $i \in \mathbb{N}$  the chain passes to the state 0 with probability  $\delta$  and to the state  $i + 1$  with probability  $1 - \delta$ . With transition probabilities so defined, the chain possesses a unique stationary distribution  $M_0$  on

the set  $\mathbb{N}$ , which can be calculated explicitly using e.g. [17, Theorem VIII.4.1], and is as follows:  $M_0(0) = \delta$ ,  $M_0(k) = \delta(1 - \delta)^k$ , for all  $k \in \mathbb{N}$ . Take this distribution as the initial distribution over the states.

The function  $f_0$  maps the states to the output alphabet  $\{0, 1\}$  as follows:  $f_0(i) = 1$  for every  $i \in \mathbb{N}$ . Let  $s_t$  be the state of the chain at time  $t$ . The process  $\rho_0$  is defined as  $\rho_0 = f_0(s_t)$  for  $t \in \mathbb{N}$ . As a result of this definition, the process  $\rho_0$  simply outputs 1 with probability 1 on every time step (however, by using different functions  $f$  we will have less trivial processes in the sequel). Clearly, the constructed process is stationary ergodic and a B-process. So, we have defined the chain  $m_0$  (and the process  $\rho_0$ ) up to a parameter  $\delta$ .

*Step 1.1.* We begin with the process  $\rho_0$  and the chain  $m_0$  of the previous step. Since the test D is asymptotically correct we will have

$$\mathbf{E}_{\rho_0 \times \rho_0} D_{t_0}((x_1, \dots, x_{t_0}), (y_1, \dots, y_{t_0})) < \varepsilon,$$

from some  $t_0$  on, where both samples  $x_i$  and  $y_i$  are generated by  $\rho_0$  (that is, both samples consist of 1s only). Let  $k_0$  be such an index that the chain  $m_0$  starting from the state 0 with probability 1 does not reach the state  $k_0 - 1$  by time  $t_0$  (we can take  $k_0 = t_0 + 2$ ).

Construct two processes  $\rho_{u1}$  and  $\rho_{d1}$  as follows. They are also based on the Markov chain  $m_0$ , but the functions  $f$  are different. The function  $f_{u1} : \mathbb{N} \rightarrow \{0, 1\}$  is defined as follows:  $f_{u1}(i) = f_0(i) = 1$  for  $i \leq k_0$  and  $f_{u1}(i) = 0$  for  $i > k_0$ . The function  $f_{d1}$  is identically 1 ( $f_{d1}(i) = 1, i \in \mathbb{N}$ ). The processes  $\rho_{u1}$  and  $\rho_{d1}$  are defined as  $\rho_{u1} = f_{u1}(s_t)$  and  $\rho_{d1} = f_{d1}(s_t)$  for  $t \in \mathbb{N}$ . Thus the process  $\rho_{d1}$  will again produce only 1s, but the process  $\rho_{u1}$  will occasionally produce 0s.

*Step 1.2.* Being run on two samples generated by the processes  $\rho_{u1}$  and  $\rho_{d1}$  which both start from the state 0, the test  $D_n$  on the first  $t_0$  steps produces many 0s, since on these first  $k_0$  states all the functions  $f$ ,  $f_{u1}$  and  $f_{d1}$  coincide. However, since the processes are different and the test is asymptotically correct (by assumption), the test starts producing 1s, until by a certain time step  $t_1$  almost all answers are 1s. Next we will construct the process  $\rho_2$  by “gluing” together  $\rho_{u1}$  and  $\rho_{d1}$  and continuing them in such a way that, being run on two samples produced by  $\rho_2$  the test first produces 0s (as if the samples were drawn from  $\rho_0$ ), then, with probability close to 1/2 it will produce many 1s (as if the samples were from  $\rho_{u1}$  and  $\rho_{d1}$ ) and then again 0s.

The process  $\rho_2$  is the pivotal point of the construction, so we give it in some detail. On step 1.2a we present the construction of the process, and on step 1.2b we show that this process is a B-process by demonstrating that it is equivalent to a (deterministic) function of a Markov chain.

*Step 1.2a.* Let  $t_1 > t_0$  be such a time index that

$$\mathbf{E}_{\rho_{u1} \times \rho_{d1}} D_{t_1}((x_1, \dots, x_{t_1}), (y_1, \dots, y_{t_1})) > 1 - \varepsilon,$$

where the samples  $x_i$  and  $y_i$  are generated by  $\rho_{u1}$  and  $\rho_{d1}$  correspondingly (the samples are generated independently; that is, the process are based on two independent copies of the Markov chain  $m_0$ ). Let  $k_1 > k_0$  be such an index that the chain  $m$  starting from the state 0 with probability 1 does not reach the state  $k_1 - 1$  by time  $t_1$ .

Construct the process  $\rho_2$  as follows (see fig. 1). It is based on a chain  $m_2$  on which Markov assumption is violated. The transition probabilities on states  $0, \dots, k_0$  are the same as for the Markov chain  $m$  (from each state return to 0 with probability  $\delta$  or go to the next state with probability  $1 - \delta$ ).

There are two “special” states: the “switch”  $S_2$  and the “reset”  $R_2$ . From the state  $k_0$  the chain passes with probability  $1 - \delta$  to the “switch” state  $S_2$ . The switch  $S_2$  can itself have two values: *up* and *down*. If  $S_2$  has the value *up* then from  $S_2$  the chain passes to the state  $u_{k_0+1}$  with probability 1, while if  $S_2 = \textit{down}$  the chain goes to  $d_{k_0+1}$ , with probability 1. If the chain reaches the state  $R_2$  then the value of  $S_2$  is set to *up* with probability 1/2 and with probability 1/2 it is set to *down*. In other words, the first transition from  $S_2$  is random (either to  $u_{k_0+1}$  or to  $d_{k_0+1}$  with equal probabilities) and then this decision is remembered until the “reset” state  $R_2$  is visited, whereupon the switch again assumes the values *up* and *down* with equal probabilities.

The rest of the transitions are as follows. From each state  $u_i, k_0 \leq i \leq k_1$  the chain passes to the state 0 with probability  $\delta$  and to the next state  $u_{i+1}$  with probability  $1 - \delta$ . From the state  $u_{k_1}$  the process goes with probability  $\delta$  to 0 and with probability  $1 - \delta$  to the “reset” state  $R_2$ . The same with states  $d_i$ : for

Figure 1: The processes  $m_2$  and  $\rho_2$ . The states are depicted as circles, the arrows symbolize transition probabilities: from every state the process returns to 0 with probability  $\delta$  or goes to the next state with probability  $1 - \delta$ . From the switch  $S_2$  the process passes to the state indicated by the switch (with probability 1); here it is the state  $u_{k_0+1}$ . When the process passes through the reset  $R_2$  the switch  $S_2$  is set to either *up* or *down* with equal probabilities. (Here  $S_2$  is in the position *up*.) The function  $f_2$  is 1 on all states except  $u_{k_0+1}, \dots, u_{k_1}$  where it is 0;  $f_2$  applied to the states output by  $m_2$  defines  $\rho_2$ .

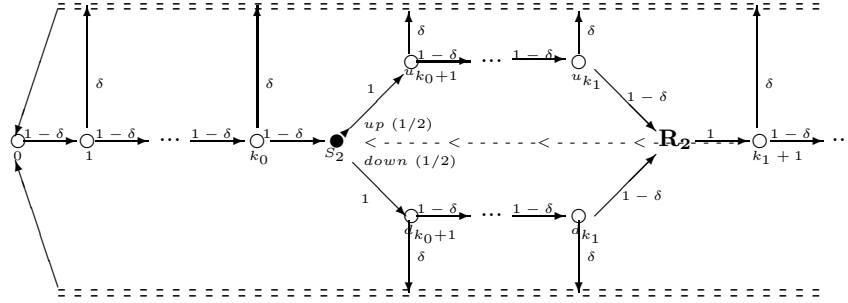
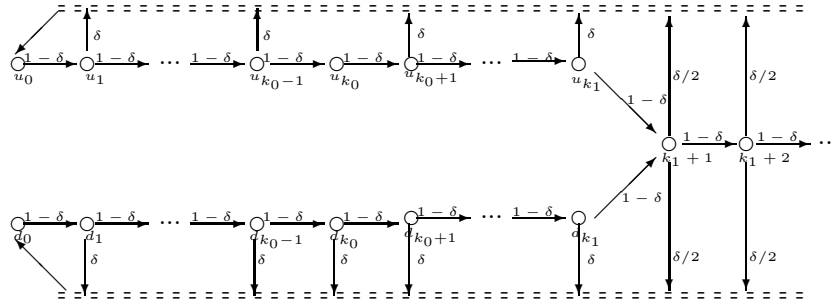


Figure 2: The process  $m'_2$ . The function  $f_2$  is 1 everywhere except the states  $u_{k_0+1}, \dots, u_{k_1}$ , where it is 0.



$k_0 < i \leq k_1$  the process returns to 0 with probability  $\delta$  or goes to the next state  $d_{i+1}$  with probability  $1 - \delta$ , where the next state for  $d_{k_1}$  is the “reset” state  $R_2$ . From  $R_2$  the process goes with probability 1 to the state  $k_1 + 1$  where from the chain continues ad infinitum: to the state 0 with probability  $\delta$  or to the next state  $k_1 + 2$  etc. with probability  $1 - \delta$ .

The initial distribution on the states is defined as follows. The probabilities of the states  $0..k_0, k_1 + 1, k_1 + 2, \dots$  are the same as in the Markov chain  $m_0$ , that is,  $\delta(1 - \delta)^j$ , for  $j = 0..k_0, k_1 + 1, k_1 + 2, \dots$ . For the states  $u_j$  and  $d_j$ ,  $k_0 < j \leq k_1$  define their initial probabilities to be 1/2 of the probability of the corresponding state in the chain  $m_0$ , that is  $m_2(u_j) = m_2(d_j) = m_0(j)/2 = \delta(1 - \delta)^j/2$ . Furthermore, if the chain starts in a state  $u_j$ ,  $k_0 < j \leq k_1$ , then the value of the switch  $S_2$  is *up*, and if it starts in the state  $d_j$  then the value of the switch  $S_2$  is *down*, whereas if the chain starts in any other state then the probability distribution on the values of the switch  $S_2$  is 1/2 for either *up* or *down*.

The function  $f_2$  is defined as follows:  $f_2(i) = 1$  for  $0 \leq i \leq k_0$  and  $i > k_1$  (before the switch and after the reset);  $f_2(u_i) = 0$  for all  $i$ ,  $k_0 < i \leq k_1$  and  $f_2(d_i) = 1$  for all  $i$ ,  $k_0 < i \leq k_1$ . The function  $f_2$  is undefined on  $S_2$  and  $R_2$ , therefore there is no output on these states (we also assume that passing through  $S_2$  and  $R_2$  does not increment time). As before, the process  $\rho_2$  is defined as  $\rho_2 = f_2(s_t)$  where  $s_t$  is the state of  $m_2$  at time  $t$ , omitting the states  $S_2$  and  $R_2$ . The resulting process is illustrated on fig. 1.

*Step 1.2b.* To show that the process  $\rho_2$  is stationary ergodic and a  $B$ -process, we will show that it is equivalent to a function of a stationary ergodic Markov chain, whereas all such process are known to be  $B$  (e.g. [16]). The construction is as follows (see fig. 2). This chain has states  $k_1 + 1, \dots$  and also  $u_0, \dots, u_{k_0}, u_{k_0+1}, \dots, u_{k_1}$  and  $d_0, \dots, d_{k_0}, d_{k_0+1}, \dots, d_{k_1}$ . From the states  $u_i$ ,  $i = 0, \dots, k_1$  the chain passes

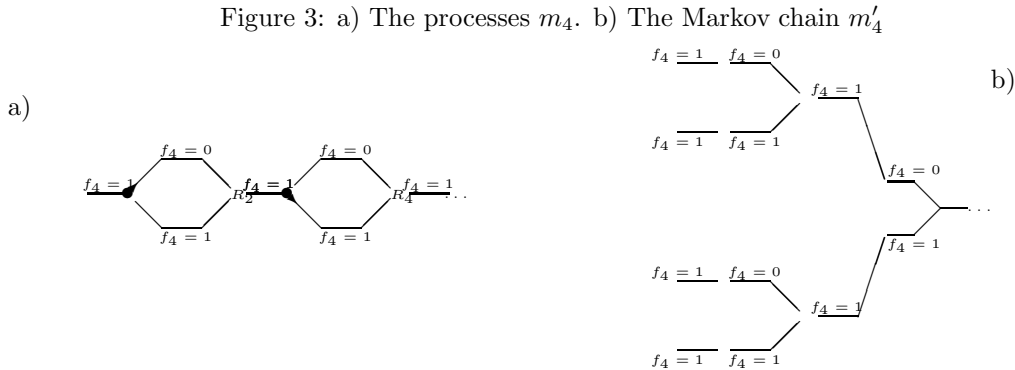
with probability  $1 - \delta$  to the next state  $u_{i+1}$ , where the next state for  $u_{k_1}$  is  $k + 1$  and with probability  $\delta$  returns to the state  $u_0$  (and not to the state 0). Transitions for the state  $d_0, \dots, d_{k_1-1}$  are defined analogously. Thus the states  $u_{k_i}$  correspond to the state *up* of the switch  $S_2$  and the states  $d_{k_i}$  — to the state *down* of the switch. Transitions for the states  $k + 1, k + 2, \dots$  are defined as follows: with probability  $\delta/2$  to the state  $u_0$ , with probability  $\delta/2$  to the state  $d_0$ , and with probability  $1 - \delta$  to the next state. Thus, transitions to 0 from the states with indices greater than  $k_1$  corresponds to the reset  $R_2$ . Clearly, the chain  $m'_2$  as defined possesses a unique stationary distribution  $M_2$  over the set of states and  $M_2(i) > 0$  for every state  $i$ . Moreover, this distribution is the same as the initial distribution on the states of the chain  $m_0$ , except for the states  $u_i$  and  $d_i$ , for which we have  $m'_2(u_i) = m'_2(d_i) = m_0(i)/2 = \delta(1 - \delta)^i/2$ , for  $0 \leq i \leq k_0$ . We take this distribution as its initial distribution on the states of  $m'_2$ . The resulting process  $m'_2$  is stationary ergodic, and a  $B$ -process, since it is a function of a Markov chain [16]. It is easy to see that if we define the function  $f_2$  on the states of  $m'_2$  as 1 on all states except  $u_{k_0+1}, \dots, u_{k_1}$ , then the resulting process is exactly the process  $\rho_2$ . Therefore,  $\rho_2$  is stationary ergodic and a  $B$ -process.

*Step 1.k.* As before, we can continue the construction of the processes  $\rho_{u_3}$  and  $\rho_{d_3}$ , that start with a segment of  $\rho_2$ . Let  $t_2 > t_1$  be a time index such that

$$\mathbf{E}_{\rho_2 \times \rho_2} D_{t_2} < \varepsilon,$$

where both samples are generated by  $\rho_2$ . Let  $k_2 > k_1$  be such an index that when starting from the state 0 the process  $m_2$  with probability 1 does not reach  $k_2 - 1$  by time  $t_2$  (equivalently: the process  $m'_2$  does not reach  $k_2 - 1$  when starting from either 0,  $u_0$  or  $d_0$ ). The processes  $\rho_{u_3}$  and  $\rho_{d_3}$  are based on the same process  $m_2$  as  $\rho_2$ . The functions  $f_{u_3}$  and  $f_{d_3}$  coincide with  $f_2$  on all states up to the state  $k_2$  (including the states  $u_i$  and  $d_i$ ,  $k_0 < i \leq k_1$ ). After  $k_2$  the function  $f_{u_3}$  outputs 0s while  $f_{d_3}$  outputs 1s:  $f_{u_3}(i) = 0$ ,  $f_{d_3}(i) = 1$  for  $i > k_2$ .

Furthermore, we find a time  $t_3 > t_2$  by which we have  $\mathbf{E}_{\rho_{u_3} \times \rho_{d_3}} D_{t_3} > 1 - \varepsilon$ , where the samples are generated by  $\rho_{u_3}$  and  $\rho_{d_3}$ , which is possible since  $D$  is consistent. Next, find an index  $k_3 > k_2$  such that the process  $m_2$  does not reach  $k_3 - 1$  with probability 1 if the processes  $\rho_{u_3}$  and  $\rho_{d_3}$  are used to produce two independent sequences and both start from the state 0. We then construct the process  $\rho_4$  based on a (non-Markovian) process  $m_4$  by “gluing” together  $\rho_{u_3}$  and  $\rho_{d_3}$  after the step  $k_3$  with a switch  $S_4$  and a reset  $R_4$  exactly as was done when constructing the process  $\rho_2$ . The process  $m_4$  is illustrated on fig. 3a). The process  $m_4$  can be shown to be equivalent to a Markov chain  $m'_4$ , which is constructed analogously to the chain  $m'_2$  (see fig. 3b). Thus, the process  $\rho_4$  can be shown to be a  $B$ -process.



Proceeding this way we can construct the processes  $\rho_{2j}$ ,  $\rho_{u_{2j+1}}$  and  $\rho_{d_{2j+1}}$ ,  $j \in \mathbb{N}$  choosing the time steps  $t_j > t_{j-1}$  so that the expected output of the test approaches 0 by the time  $t_j$  being run on two samples produced by  $\rho_j$  for even  $j$ , and approaches 1 by the time  $t_j$  being run on samples produced by  $\rho_{u_j}$  and  $\rho_{d_j}$  for odd  $j$ :

$$\mathbf{E}_{\rho_{2j} \times \rho_{2j}} D_{t_{2j}} < \varepsilon \tag{2}$$

and

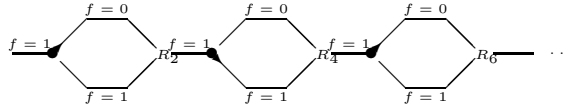
$$\mathbf{E}_{\rho_{u_{2j+1}} \times \rho_{d_{2j+1}}} D_{t_{2j+1}} > (1 - \varepsilon). \tag{3}$$

For each  $j$  the number  $k_j > k_{j-1}$  is selected in a such a way that the state  $k_j - 1$  is not reached (with probability 1) by the time  $t_j$  when starting from the state 0. Each of the processes  $\rho_{2j}$ ,  $\rho_{u_{2j+1}}$  and  $\rho_{d_{2j+1}}$ ,  $j \in \mathbb{N}$  can be shown to be stationary ergodic and a  $B$ -process by demonstrating equivalence to a Markov chain, analogously to the Step 1.2. The initial state distribution of each of the processes  $\rho_t$ ,  $t \in \mathbb{N}$  is  $M_t(k) = \delta(1 - \delta)^k$  and  $M_t(u_k) = M_t(d_k) = \delta(1 - \delta)^k/2$  for those  $k \in \mathbb{N}$  for which the corresponding states are defined.

*Step 2.* Having defined  $k_j$ ,  $j \in \mathbb{N}$  we can define the process  $\rho$ . The construction is given on Step 2a, while on Step 2b we show that  $\rho$  is stationary ergodic and a  $B$ -process, by showing that it is the limit of the sequence  $\rho_{2j}$ ,  $j \in \mathbb{N}$ .

*Step 2a.* The process  $\rho$  can be constructed as follows (see fig. 4). The construction is based on

Figure 4: The processes  $m_\rho$  and  $\rho$ . The states are on horizontal lines. The function  $f$  being applied to the states of  $m_\rho$  defines the process  $\rho$ . Its value is 0 on the states on the upper lines (states  $u_{k_{2j}+1}, \dots, u_{k_{2j+1}}$ , where  $k \in \mathbb{N}$ ) and 1 on the rest of the states.



the (non-Markovian) process  $m_\rho$  that has states  $0, \dots, k_0, k_{2j+1} + 1, \dots, k_{2(j+1)}, u_{k_{2j}+1}, \dots, u_{k_{2j+1}}$  and  $d_{k_{2j}+1}, \dots, d_{k_{2j+1}}$  for  $j \in \mathbb{N}$ , along with switch states  $S_{2j}$  and reset states  $R_{2j}$ . Each switch  $S_{2j}$  diverts the process to the state  $u_{k_{2j}+1}$  if the switch has value *up* and to  $d_{k_{2j}+1}$  if it has the value *down*. The reset  $R_{2j}$  sets  $S_{2j}$  to *up* with probability 1/2 and to *down* also with probability 1/2. From each state that is neither a reset nor a switch, the process goes to the next state with probability  $1 - \delta$  and returns to the state 0 with probability  $\delta$  (cf. Step 1k).

The initial distribution  $M_\rho$  on the states of  $m_\rho$  is defined as follows. For every state  $i$  such that  $0 \leq i \leq k_0$  and  $k_{2j+1} < i \leq k_{2j+2}$ ,  $j = 0, 1, \dots$ , define the initial probability of the state  $i$  as  $M_\rho(i) = \delta(1 - \delta)^i$  (the same as in the chain  $m_0$ ), and for the sets  $u_j$  and  $d_j$  (for those  $j$  for which these sets are defined) let  $M_\rho(u_j) = M_\rho(d_j) := \delta(1 - \delta)^j/2$  (that is, 1/2 of the probability of the corresponding state of  $m_0$ ).

The function  $f$  is defined as 1 everywhere except for the states  $u_j$  (for all  $j \in \mathbb{N}$  for which  $u_j$  is defined) on which  $f$  takes the value 0. The process  $\rho$  is defined at time  $t$  as  $f(s_t)$ , where  $s_t$  is the state of  $m_\rho$  at time  $t$ .

*Step 2b.* To show that  $\rho$  is a  $B$ -process, let us first show that it is stationary. To do this, define the so-called distributional distance on the set of all stochastic processes as follows.

$$d(\mu_1, \mu_2) = \sum_{i=1}^{\infty} w_i |\mu_1((x_1, \dots, x_{|B_i|}) = B_i) - \mu_2((x_1, \dots, x_{|B_i|}) = B_i)|,$$

where  $\mu_1, \mu_2$  are any stochastic processes,  $w_k := 2^{-k}$  and  $B_i$  ranges over all tuples  $B \in \cup_{k \in \mathbb{N}} X^k$ , assuming some fixed order on this set. The set of all stochastic processes, equipped with this distance, is complete, and the set of all stationary processes is its closed subset [4]. Thus, to show that the process  $\rho$  is stationary it suffices to show that  $\lim_{j \rightarrow \infty} d(\rho_{2j}, \rho) = 0$ , since the processes  $\rho_{2j}$ ,  $j \in \mathbb{N}$ , are stationary. To do this, it is enough to demonstrate that

$$\lim_{j \rightarrow \infty} |\rho((x_1, \dots, x_{|B|}) = B) - \rho_{2j}((x_1, \dots, x_{|B|}) = B)| = 0 \quad (4)$$

for each  $B \in \cup_{k \in \mathbb{N}} X^k$ . Since the processes  $m_\rho$  and  $m_{2j}$  coincide on all states up to  $k_{2j+1}$ , we have

$$|\rho(x_n = a) - \rho_{2j}(x_n = a)| = |\rho(x_1 = a) - \rho_{2j}(x_1 = a)| \leq \sum_{k > k_{2j+1}} M_\rho(k) + \sum_{k > k_{2j+1}} M_{2j}(k)$$

for every  $n \in \mathbb{N}$  and  $a \in X$ . Moreover, for any tuple  $B \in \cup_{k \in \mathbb{N}} X^k$  we obtain

$$|\rho((x_1, \dots, x_{|B|}) = B) - \rho_{2j}((x_1, \dots, x_{|B|}) = B)| \leq |B| \left( \sum_{k > k_{2j+1}} M_\rho(k) + \sum_{k > k_{2j+1}} M_{2j}(k) \right) \rightarrow 0$$

where the convergence follows from  $k_{2j} \rightarrow \infty$ . We conclude that (4) holds true, so that  $d(\rho, \rho_{2j}) \rightarrow 0$  and  $\rho$  is stationary.

To show that  $\rho$  is a  $B$ -process, we will demonstrate that it is the limit of the sequence  $\rho_{2k}$ ,  $k \in \mathbb{N}$  in the  $\bar{d}$  distance (which was only defined for stationary processes). Since the set of all  $B$ -process is a closed subset of all stationary processes, it will follow that  $\rho$  itself is a  $B$ -process. (Observe that this way we get ergodicity of  $\rho$  “for free”, since the set of all ergodic processes is closed in  $\bar{d}$  distance, and all the processes  $\rho_{2j}$  are ergodic.) In order to show that  $\bar{d}(\rho, \rho_{2k}) \rightarrow 0$  we have to find for each  $j$  a processes  $\nu_{2j}$  on pairs  $(x_1, y_1), (x_2, y_2), \dots$ , such that  $x_i$  are distributed according to  $\rho$  and  $y_i$  are distributed according to  $\rho_{2j}$ , and such that  $\lim_{j \rightarrow \infty} \nu_{2j}(x_1 \neq y_1) = 0$ . Construct such a coupling as follows. Consider the chains  $m_\rho$  and  $m_{2j}$ , which start in the same state (with initial distribution being  $M_\rho$ ) and always take state transitions together, where if the process  $m_\rho$  is in the state  $u_t$  or  $d_t$ ,  $t \geq k_{2j+1}$  (that is, one of the states which the chain  $m_{2j}$  does not have) then the chain  $m_{2j}$  is in the state  $t$ . The first coordinate of the process  $\nu_{2j}$  is obtained by applying the function  $f$  to the process  $m_\rho$  and the second by applying  $f_{2j}$  to the chain  $m_{2j}$ . Clearly, the distribution of the first coordinate is  $\rho$  and the distribution of the second is  $\rho_{2j}$ . Since the chains start in the same state and always take state transitions together, and since the chains  $m_\rho$  and  $m_{2j}$  coincide up to the state  $k_{2j+1}$  we have  $\nu_{2j}(x_1 \neq y_1) \leq \sum_{k > k_{2j+1}} M_\rho(k) \rightarrow 0$ . Thus,  $\bar{d}(\rho, \rho_{2j}) \rightarrow 0$ , so that  $\rho$  is a  $B$ -process.

*Step 3.* Finally, it remains to show that the expected output of the test  $D$  diverges if the test is run on two independent samples produced by  $\rho$ .

Recall that for all the chains  $m_{2j}$ ,  $m_{u_{2j+1}}$  and  $m_{d_{2j+1}}$  as well as for the chain  $m_\rho$ , the initial probability of the state 0 is  $\delta$ . By construction, if the process  $m_\rho$  starts at the state 0 then up to the time step  $k_{2j}$  it behaves exactly as  $\rho_{2j}$  that has started at the state 0. In symbols, we have

$$E_{\rho \times \rho}(D_{t_{2j}} | s_0^x = 0, s_0^y = 0) = E_{\rho_{2j} \times \rho_{2j}}(D_{t_{2j}} | s_0^x = 0, s_0^y = 0) \quad (5)$$

for  $j \in \mathbb{N}$ , where  $s_0^x$  and  $s_0^y$  denote the initial states of the processes generating the samples  $x$  and  $y$  correspondingly.

We will use the following simple decomposition

$$\mathbf{E}(D_{t_j}) = \delta^2 \mathbf{E}(D_{t_j} | s_0^x = 0, s_0^y = 0) + (1 - \delta^2) \mathbf{E}(D_{t_j} | s_0^x \neq 0 \text{ or } s_0^y \neq 0), \quad (6)$$

(5), and (2) we have

$$\begin{aligned} \mathbf{E}_{\rho \times \rho}(D_{t_{2j}}) &\leq \delta^2 \mathbf{E}_{\rho \times \rho}(D_{t_{2j}} | s_0^x = 0, s_0^y = 0) + (1 - \delta^2) \\ &= \delta^2 \mathbf{E}_{\rho_{2j} \times \rho_{2j}}(D_{t_{2j}} | s_0^x = 0, s_0^y = 0) + (1 - \delta^2) \\ &\leq \mathbf{E}_{\rho_{2j} \times \rho_{2j}} + (1 - \delta^2) < \varepsilon + (1 - \delta^2). \end{aligned} \quad (7)$$

For odd indices, if the process  $\rho$  starts at the state 0 then (from the definition of  $t_{2j+1}$ ) by the time  $t_{2j+1}$  it does not reach the reset  $R_{2j}$ ; therefore, in this case the value of the switch  $S_{2j}$  does not change up to the time  $t_{2j+1}$ . Since the definition of  $m_\rho$  is symmetric with respect to the values *up* and *down* of each switch, the probability that two samples  $x_1, \dots, x_{t_{2j+1}}$  and  $y_1, \dots, y_{t_{2j+1}}$  generated independently by (two runs of) the process  $\rho$  produced different values of the switch  $S_{2j}$  when passing through it for the first time is 1/2. In other words, with probability 1/2 two samples generated by  $\rho$  starting at the state 0 will look by the time  $t_{2j+1}$  as two samples generated by  $\rho_{u_{2j+1}}$  and  $\rho_{d_{2j+1}}$  that has started at state 0. Thus

$$E_{\rho \times \rho}(D_{t_{2j+1}} | s_0^x = 0, s_0^y = 0) \geq \frac{1}{2} E_{\rho_{u_{2j+1}} \times \rho_{d_{2j+1}}}(D_{t_{2j+1}} | s_0^x = 0, s_0^y = 0) \quad (8)$$



for  $j \in \mathbb{N}$ . Using this, (6), and (3) we obtain

$$\begin{aligned} \mathbf{E}_{\rho \times \rho}(D_{t_{2j+1}}) &\geq \delta^2 \mathbf{E}_{\rho \times \rho}(D_{t_{2j+1}} | s_0^x = 0, s_0^y = 0) \\ &\geq \frac{1}{2} \delta^2 \mathbf{E}_{\rho_{2j+1} \times \rho_{2j+1}}(D_{t_{2j+1}} | s_0^x = 0, s_0^y = 0) \\ &\geq \frac{1}{2} (\mathbf{E}_{\rho_{2j+1} \times \rho_{2j+1}}(D_{t_{2j+1}}) - (1 - \delta^2)) > \frac{1}{2}(\delta^2 - \varepsilon). \end{aligned} \quad (9)$$

Taking  $\delta$  large and  $\varepsilon$  small (e.g.  $\delta = 0.9$  and  $\varepsilon = 0.1$ ), we can make the bound (7) close to 0 and the bound (9) close to  $1/2$ , and the expected output of the test will cross these values infinitely often. Therefore, we have shown that the expected output of the test  $D$  diverges on two independent runs of the process  $\rho$ , contradicting the consistency of  $D$ . This contradiction concludes the proof.

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