

# Towards a Better Understanding of Space-Time Causality: Kolmogorov Complexity and Causality as a Matter of Degree

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**Abstract**—Space-time causality is one of the fundamental notions of modern physics; however, it is difficult to define in observational physical terms. Intuitively, the fact that a space-time event  $e = (t, x)$  can causally influence an event  $e' = (t', x')$  means that what we do in the vicinity of  $e$  changes what we observe at  $e'$ . If we had two copies of the Universe, we could perform some action at  $e$  in one copy but not in another copy; if we then observe the difference at  $e'$ , this would be an indication of causality. However, we only observe one Universe, in which we either perform the action or we do not. At first glance, it may seem that in this case, there is no meaningful way to provide an operational definition of causality. In this paper, we show that such a definition is possible if we use the notions of algorithmic randomness and Kolmogorov complexity. The resulting definition leads to a somewhat unexpected consequence: that space-time causality is a matter of degree.

## I. DEFINING CAUSALITY IS IMPORTANT

**Space-time causality is important.** Causality relation between space-time events (i.e., points in space-time) is one of the fundamental notions of physics; see, e.g., [1], [3]. Because of this, many fundamental physical theories describe, among other things, the causality relation between space-time events.

**According to modern physics, space-time causality relation is non-trivial.** In Newton's physics, it was assumed that influences can propagate with an arbitrary speed, constituting, in effect, immediate action-at-a-distance. Under this assumption, an event  $e = (t, x)$  occurring at moment  $t$  at location  $x$  can influence an event  $e' = (t', x')$  occurring at moment  $t'$  at location  $x'$  if and only if the second event occurs later than the first one, i.e., if and only if  $t < t'$ .

In special relativity, the speeds of all the processes are limited by the speed of light  $c$ . In this theory, an event  $e = (t, x)$  can influence an event  $e' = (t', x')$  if during the time  $t' - t$ , the faster possible process – light – can cover the distance  $d(x, x')$  between locations  $x$  and  $x'$ , i.e., if

$$c \cdot (t' - t) \geq d(x, x').$$

In the general relativity theory, the space-time is curved, so the corresponding causality relation is even more com-

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plex. This relation is also complex in alternative gravitation theories; see, e.g., [3].

**Need for experimental verification of space-time causality.** Different theories, in general, make different predictions about the causality relation. So, to experimentally verify fundamental physical theories, we need to be able to experimentally verify the corresponding space-time causality relation. In other words, we must be able to experimentally check, for every two space-time events  $a$  and  $b$ , whether the event  $a$  can causally influence the event  $b$ .

**Need for a theory-free verification of space-time causality.** Since the space-time causality relation is fundamental, more fundamental than specific partial differential equations that describe the physical fields and/or their relation with space-time, it is desirable to be able to experimentally check this causality relation in a theory-free way, without invoking other fields and corresponding differential equations.

In this paper, we describe a possible way of such theory-free experimental validation of space-time causality.

*Comment.* Some of the ideas described in this paper first appeared in [4].

## II. DEFINING CAUSALITY: CHALLENGE

**Intuitive meaning of space-time causality.** Intuitively, the fact that a space-time event  $e$  can causally influence an event  $e'$  means that:

- what we do in the vicinity of  $e$
- changes what we observe at  $e'$ .

**How to transform this meaning into a definition: a hypothetical idea.** The above intuitive meaning of space-time causality can easily lead to a observational definition if we had two (or more) copies of the Universe. In this case, to check that  $e$  can causally influence  $e'$ , we could do the following (see, e.g., [5]):

- in one copy of the Universe, we perform some action at  $e$ , and
- we do not perform this action in the second copy of the Universe.

If the resulting states at  $e'$  are different in the two copies of the Universe, this would be an indication of causality relation between  $e$  and  $e'$ .

*Comment.* This interpretation of causality is known as a *counterfactual* interpretation; see, e.g., [6].

**Can we make this idea practical?** In reality, we only observe one Universe, in which we either perform the action or we do not.

At first glance, it may seem that in this case, there is no meaningful way to provide an operational definition of space-time causality.

**Our idea.** In this paper, we show that a meaningful operational definition of space-time causality is possible if we use the notions of algorithmic randomness and Kolmogorov complexity. Before we explain our idea, let us briefly recall the corresponding notions.

### III. ALGORITHMIC RANDOMNESS AND KOLMOGOROV COMPLEXITY: A BRIEF REMINDER

**Motivation for algorithmic randomness and Kolmogorov complexity.** Intuitively, we know that some sequences of 0s and 1s (or, equivalently, heads and tails) are random, while other sequences are not random. For example, intuitively, if we flip a fair coin 4 times, we can get a sequence 0000 of all heads. However, if we flip a coin 1000 times and still get all heads, common sense tells us that this coin is not fair. Similarly, common sense tells us that, if we repeatedly flip a fair coin, we cannot expect a periodic sequence 0101...01 (repeated 500 times).

In the traditional probability theory, it is not possible to formally describe this intuitive difference between random and non-random sequences. To provide such a formalization, in the 1960s, A. N. Kolmogorov, one of the world leading specialists in probability theory and mathematical statistics, proposed the following idea (for details, see, e.g., [2]).

**Main idea behind algorithmic randomness and Kolmogorov complexity.** According to Kolmogorov, the intuitive reason why a sequence consisting of all 0s is not random is that it has a simple structure; in other words, this sequence can be generated by a very simple for-loop program. Similarly, a sequence consisting of a sequence 01 repeated 500 times is simple to generate: just make a for-loop. In contrast, a truly random sequence should not have a simple structure – that would enable us to generate it by using some short program: in effect, the shortest way to print this truly random sequence is to actually print it bit-by-bit: `printf(01...)`.

This idea leads to the following way of detecting whether a given finite sequence  $x$  of 0s and 1s is random or not:

- if this sequence  $x$  can be generated by a short program – i.e., a program whose length is much smaller than the length  $\text{len}(x)$  of this sequence – then  $x$  is clearly not random;
- vice versa, if the only way to generate a sequence  $x$  is to use a program whose length is at least  $\text{len}(x)$ , then this sequence  $x$  is truly random.

To make this distinction, we need to know, for each sequence  $x$ , the shortest length of a program that generates  $x$ . This shortest length is known as the *Kolmogorov complexity* of

the string  $x$  and denoted by  $K(x)$ . In terms of Kolmogorov complexity:

- if  $K(x) \ll \text{len}(x)$ , then  $x$  is not random;
- if  $K(x) \approx \text{len}(x)$ , then  $x$  is random.

For example, we can select a small integer  $C > 0$  (e.g.,  $C = 10$ ), and define a sequence  $x$  to be *random* if

$$K(x) \geq \text{len}(x) - C.$$

**Definition 1.** Let a programming language be fixed. By a Kolmogorov complexity  $K(x)$  of a finite binary string  $x$ , we mean the shortest length of a program that generates  $x$ :

$$K(x) \stackrel{\text{def}}{=} \min\{\text{len}(p) : p \text{ generates } x\}.$$

**Definition 2.** Let an integer  $C > 0$  be fixed. We say that a string  $x$  is random if  $K(x) \geq \text{len}(x) - C$ .

*Historical comment.* Simultaneously with Kolmogorov, similar ideas were proposed by R. Solomonoff and G. Chaitin [2].

*Comment.* The length of a program depends on the programming language. However, as Kolmogorov has shown, the definitions  $K_1(x)$  and  $K_2(x)$  of Kolmogorov complexity based on two different languages differ by a constant:  $|K_1(x) - K_2(x)| \leq C_{12}$  for all  $x$ . Thus, in effect, different programming languages lead to the same definition of a random sequence.

**The corresponding notion of independence.** In probability theory, in addition to analyzing what is *random* and what is not, it is also important to decide when the two events are *independent* and when they are not. Once we have two finite binary sequences  $x$  and  $y$ , the idea that  $y$  is independent on  $x$  can be described in a similar way:

- if  $y$  is independent on  $x$ , then knowing  $x$  does not help us generate  $y$ ;
- in contrast, if  $y$  depends on  $x$ , then knowing  $x$  can help us compute  $y$ .

For example, if we know the locations and velocities  $x$  of a mechanical system at some moment of time  $t$ , we can use this information to easily compute the locations and velocities  $y$  at the next moment of time  $t + \Delta t$ . In contrast, an irrelevant information  $x$  (e.g., locations and velocities of particles on another planet) does not help in computing  $y$ .

To formalize this intuition, we should consider programs that use  $x$  as an input to generate  $y$ .

**Definition 3.** Let a programming language be fixed. By a relative Kolmogorov complexity  $K(y|x)$  of a finite binary string  $y$  in relation to a binary string  $x$ , we mean the shortest length of a program that, when using  $x$  as an input, generates  $y$ :

$$K(y|x) \stackrel{\text{def}}{=} \min\{\text{len}(p) : p(x) \text{ generates } y\}.$$

*Comment.* Intuitively, if using  $x$  helps to compute  $y$ , i.e., if  $K(y|x) \ll K(y)$ , this means that  $y$  depends on  $x$ . Vice versa, if using  $x$  does not help to compute  $y$ , i.e., if  $K(y|x) \approx K(y)$ , this means that  $x$  and  $y$  are independent. We can describe this in a way similar to the above definition of randomness:

**Definition 4.** Let an integer  $C > 0$  be fixed.

- We say that a string  $y$  is independent of the string  $x$  if

$$K(y|x) \geq K(y) - C.$$

- We say that a string  $y$  is dependent on the string  $x$  if

$$K(y|x) < K(y) - C.$$

#### IV. HOW TO DEFINE SPACE-TIME CAUSALITY: ANALYSIS OF THE PROBLEM AND THE RESULTING DEFINITION

**First seeming reasonable idea.** At first glance, the above notion of dependence can already lead to a natural definition of space-time causality:

- First, we perform some measurements and observations in the vicinity of the event  $e$ . Since most nowadays measuring instruments are computer-connected, each such measurement produces a computer-readable output. In the computer, everything is represented as a sequence of 0s and 1s, so the results of all the measurements and observations will also be represented as a sequence  $x$  of 0s and 1s.
- We also perform measurements and observations in the vicinity of the event  $e'$ , and also produce a sequence  $x'$  of 0s and 1s.
- If  $x'$  depends on  $x$ , i.e., if  $K(x'|x) \ll K(x')$ , then we claim that  $e$  can causally influence  $e'$ .

**Alas, this idea does not always work.** Yes, if  $e$  can causally influence  $e'$ , then we indeed expect that knowing what happened at  $e$  can help us predict what is happening at  $e'$ . However, the inverse is not necessarily true: we may have identical observations  $x = x'$  at events  $e$  and  $e'$  simply because they are both caused by the same event  $e''$  from the joint past of events  $e$  and  $e'$ .

For example, if two people at different locations are watching the same movie, then their observations are identical, but not because they causally influence each other, but because they are both influenced by a past event  $e''$  (of making this movie).

**How to transform the above idea into a working definition.** According to modern physics, the Universe is quantum in nature. For many measurements involving microscopic objects, we cannot predict the exact measurement results, we can only predict probabilities of different outcomes. The actual observations are truly random.

Moreover, for each space-time event  $e$ , we can always set up such random-producing experiments in the small vicinity of  $e$ , and generate a random sequence  $r_e$ . For example, we can locally set up a Stern-Gerlach experiment (see, e.g.,

[1]), a quantum experiment that generates a truly random sequence.

This random sequence can affect *future* results, so if we know this random sequence, it may help us predict future observations. So, if  $e$  can causally influence  $e'$ , then for some observations  $x'$  performed in the small vicinity of  $e'$ , we have  $K(x'|r_e) \ll K(x')$ .

However, it is clear that this sequence cannot affect the measurement results which are in the *past* (or, more generally, not in the future) of the event  $e$ . So, if  $e$  cannot causally influence  $e'$ , then observations  $x'$  made in the vicinity of  $e'$  are independent on  $r_e$ :  $K(x'|r_e) \approx K(x')$ . So, we arrive at the following semi-formal definition:

**Definition 5.** For each space-time event  $e$ , let  $r_e$  denote a random sequence that is generated by an experiment performed in the small vicinity of  $e$ . We say that the event  $e$  can causally influence the event  $e'$  if for some observations  $x'$  performed in the small vicinity of  $e'$ , we have

$$K(x'|r_e) \ll K(x').$$

*Historical comment.* Our definition follows the ideas of causality as mark transmission [6], [7], with the random sequence as a mark.

*Discussion.* We have argued that if  $e$  does not causally influence  $e'$ , then, no matter what we measure in the vicinity of the event  $e'$ , we get  $K(x'|r_e) \approx K(x')$  – so in these cases, the above definition is in accordance with the physical intuition.

On the other hand, if  $e$  can causally influence  $e'$ , this means that we can send a signal from  $e$  to  $e'$ , and as this signal, we send all the bits forming the random sequence  $r_e$ . The signal  $x'$  received in the vicinity of  $e'$  will thus be identical to  $r_e$ , so generating  $x'$  based on  $r_e$  does not require any computations at all:  $K(x'|r_e) = 0$ . Since the sequence  $x' = r_e$  is random, we have

$$K(x') \geq \text{len}(x') - C.$$

For a sufficiently long random sequence  $r_e = x'$ , namely for a sequence for which  $\text{len}(x') > 2C$ , we have

$$K(x') \geq \text{len}(x') - C > 2C - C = C,$$

so

$$0 = K(x'|r_e) < K(x') - C$$

and thus,

$$K(x'|r_e) \ll K(x').$$

So, in these cases, the above definition is also in accordance with the physical intuition.

V. A SOMEWHAT UNEXPECTED COROLLARY OF OUR DEFINITION: SPACE-TIME CAUSALITY IS A MATTER OF DEGREE

**Observation: space-time causality is a matter of degree.**

The above notion of randomness describes, in effect, a *degree* of randomness:

- if for some sequence  $x$ , we have  $K(x) \leq \text{len}(x) - C$  for a small integer  $C$ , while
- for another sequence  $x'$  of the same length, we only have the inequality  $K(x') \geq \text{len}(x') - C'$  for a larger integer  $C' > C$ ,

then it is reasonable to conclude that the sequence  $x$  is “more random” than the sequence  $x'$ . For example, if we start with a sequence  $x$  obtained by a truly random physical process (e.g., flipping a coin, or, better yet, a truly random quantum experiment) and start replacing the first few bits with 0s, then we get new sequences which are, intuitively, less and less random – until we replace so many bits by 0s that the sequence stops being random.

Similarly, the above definition of space-time causality seems to suggest that we can have *degrees* of causality:

- if for some pair of events  $e$  and  $e'$ , for a random sequence  $r_e$  generated in the vicinity of  $e$  and for measurement results  $x'$  produced in the vicinity of  $e'$ , we have  $K(x' | r_e) < K(x') - C$  for some large integer  $C$ , while
- for some other pair of events  $f$  and  $f'$ , for any random sequence  $r_f$  generated in the vicinity of  $e$  and for measurement results  $y'$  produced in the vicinity of  $f'$ , we only have  $K(y' | r_f) < K(y') - C'$  for some smaller integer  $C' < C$ ,

then we can say that the degree to which  $e$  can causally influence  $e'$  is larger than the degree to which  $f$  can causally influence  $f'$ .

*Comment.* While this conclusion may be unexpected from the viewpoint of traditional physics, it is in good accordance with the general idea of fuzzy logic, that everything – including causality – is a matter of degree; see, e.g., [8].

**Corresponding open problems.** It is desirable to explore possible physical meaning of such “degrees of causality”: instead of describing the space-time causality relation, we now have a function  $d(e, e')$  that, for each pair of events

for which  $e$  causally precedes  $e'$ , describes to what extent  $e$  can influence  $e'$ . Maybe this function  $d(e, e')$  is related to relativistic metric – the amount of proper time between  $e$  and  $e'$ ?

Another open problem is related to the fact that the above definition works for localized objects, objects which are located in a small vicinity of one spatial location.

In quantum physics, not all objects are localized in space-time. We can have situations when the states of two spatially separated particles are entangled. It is desirable to extend our definition to such objects as well.

VI. CONCLUSIONS

In this paper, we propose a new operationalist definition of causality between space-time events. Namely, to check whether an event  $e$  can causally influence an event  $e'$ , we:

- generate a truly random sequence  $r_e$  in the small vicinity of the event  $e$ , and
- perform observations in the small vicinity of the event  $e'$ .

If some observation results  $x'$  (obtained near  $e'$ ) *depend* on the sequence  $r_e$  (in the precise sense of dependence described in the paper), then we claim that  $e$  *can* causally influence  $e'$ . On the other hand, if all observation results  $x'$  are independent on  $r_e$ , then we claim that  $e$  *cannot* causally influence  $e'$ .

This new definition naturally leads to a conclusion that space-time causality is a matter of degree, a conclusion that is worth physical analysis.

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