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Quantum Superpositions of Causal Structures: From Foundations to New Technologies

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Abstract

This presentation provides a non-technical overview of the notion of quantum superposition of causal structures, of its applications, and of its proposed physical realizations. The conceptual underpinning for these investigations is a view of quantum theory as a new kind of probability theory. At the axiomatic level, the principles of this new kind of probability theory suggest new causal relations that have no analogue in the classical world. These new causal relations are a potential resource for new technologies, including computation and communication technology.

Keywords: quantum information, quantum causality, indefinite causal order, quantum SWITCH, foundations of quantum mechanics

1. Introduction

The subject of this presentation is causality in the quantum world. I will mostly speak about how quantum theory can be viewed as a new kind of probability theory, and how the principles of this new kind of probability theory suggest new types of causal relation that have no analogue in the classical world. I will show that these new types of causal relations are a potential resource for new technologies, including computation and communication technology. Finally, I will briefly discuss the different physical situations in which such new causal relations could occur.

2. Quantum mechanics vs quantum probability theory

Let us start with a bit of background concerning the quantum theory of probability. One of the important lessons of the last thirty years of research in the foundations of quantum mechanics is that many of the counterintuitive aspects of quantum physics have more to do with logic and probability theory than they have to do with traditional physical quantities such as position, velocity, mass, and energy (Chiribella and Spekkens 2015).

True that quantum mechanics was originally formulated in an attempt to explain the physics of atoms and of the electromagnetic radiation. Nevertheless, many of the aspects that make quantum physics so strikingly special compared to classical physics have little to do with "mechanics", and much more to do with probability theory.

For example, Bell's celebrated Theorem (Bell 1964) shows that quantum systems composed of multiple parts exhibit correlations that are impossible in the classical world. Bell's theorem holds universally, independently of which specific quantum systems we consider. It is not a consequence of the mechanics of the systems under consideration, but rather of the way in which the quantum formalism assigns probabilities to the outcomes of experiments.

For this reason, it is convenient to distinguish between "quantum mechanics" (viewed as the theory of time evolution of certain microscopic systems) and "quantum probability theory" (viewed as a set of abstract rules for assigning probabilities to the outcomes of experiments). Quantum probability theory is the language in which the contents of quantum mechanics are expressed, but in principle it can be applied to more general situations.

What I will discuss in the following refers primarily to quantum probability theory. This approach, which transcends the details of specific physical systems, is broadly adopted in the field of Quantum Information Theory.

Quantum information theory is concerned with the information-processing capabilities of *abstract physical systems*, characterized by the maximum number of states that can be distinguished without error through a single experiment. A quantum bit, or *qubit*, is an abstract quantum system with two (and only two) perfectly distinguishable states.

For the purposes of information theory, it is irrelevant whether the qubit is realized with the polarization of a single photon, the spin of a nucleus, or the electronic state of an atom. In principle, all qubits are created equal: they can all be used to perform the same logical operations, the same computations, and the same communication protocols. In this respect, quantum information theory is no different from classical information theory, where the notion of bit is applied to all classical systems with two (and only two) perfectly distinguishable states.

3. Axiomatizations of quantum probability theory

The idea of the quantum formalism as a universal language, independent of the details of the physical systems in question, is at the basis of a large project of axiomatization of quantum theory, initiated in 1936 by Garrett Birkhoff and John von Neumann (Birkhoff and von Neumann 1936).

This project led to the field of quantum logic, which produced results of high technical value, although sometimes struggled to go past its technicalities. A renewed interest in the axiomatization project came with the advent of Quantum Information, and was strongly advocated by Chris Fuchs (Fuchs 2003) and Gilles Brassard (Brassard 2005). The first result in this direction came in 2001 with the work of Lucien Hardy (Hardy 2001), who proposed a list of simple axioms concerning logical operations and the probabilistic structure of abstract physical systems. Combining these axioms with a series of reasonable assumptions on the formalism, Hardy showed that the mathematical structure of quantum probability theory can be reconstructed from a new starting point.

Following Hardy, other authors sought to reconstruct the rules of quantum probability theory without invoking *ad hoc* mathematical axioms, and without invoking mechanical notions such as those of position and momentum (Dakic and Brukner 2011, Masanes and Müller 2011, Chiribella, D'Ariano, and Perinotti 2011, Masanes, Müller, Augusiak, and Peréz-García 2012, Barnum, Müller, Ududec 2014; see also Chiribella and Spekkens 2015 and references therein).

4. The CDP axiomatization

One of the new axiomatizations was proposed by Mauro D'Ariano, Paolo Perinotti, and myself in 2010. The original work was published in Physical Review A (Chiribella, D'Ariano, and Perinotti 2011), and was recently developed into a book, published by Cambridge University Press (D'Ariano, Chiribella, and Perinotti 2017). Several non-technical presentations of this work are also available (Chiribella, D'Ariano, and Perinotti 2012; Chiribella and Yuan 2013; Chiribella and Scandolo 2015). Hereafter I will refer to this axiomatization as the *CDP axiomatization*.

The key feature of the CDP axiomatization that it reconstructs the quantum formalism from principles of informational nature. These principles concern the ability to communicate without errors, to store data with maximal efficiency, and to perform computations in a reversible way.

The CDP axiomatization is based on an abstract framework that describes networks of events, connected with one another through the transmission of physical systems. In general, every event is associated to a set of physical systems in input, and to a set of physical systems in output. For example, an event could be the collision of two particles: in this case, the two particles are the physical systems in input, and the result of the collision are the physical systems in output.

Events can occur in experiments. In general, every experiment is associated to a set of possible events, interpreted as alternative outcomes. An example of experiment is the toss of a coin, in which the possible events are "head" and "tails". It is worth stressing that we use the term "experiment" in a broad sense, without implying that an agent should be present at every stage of the process.

In our framework, a probabilistic theory consists in the specification of all possible events and all possible experiments, together with the specification of a rule that assigns probabilities to the outcomes of such experiments.

Note that the distinction between input systems and output systems implies that our networks have a privileged direction, from the input to the output. In the following, we will be interested in applications of the formalism where the input-output direction is identified with the arrow of time.

5. The Causality Principle

In the CDP axiomatization, the quantum theory of probability is reconstructed from 6 principles. The first of them is the Causality Principle, which forbids the transmission of information from the future to the past. Informally, the Causality Principle stipulates that the probability of an event in the present is independent of the choice of experiments performed in the future.

The Causality Principle is equivalent to the impossibility of modifying the state of a system in the past. In other words, the Causality Principle is the assumption of the "immodificability of the past" which gives the title to this conference.

The Causality Principle is essential in our derivation of the quantum formalism. The reason for this is very simple: the standard quantum formalism, which is found in most textbooks and is applicable to most (if not all) of the physical systems we known, satisfies the Causality Principle. For the purpose of reconstructing the standard quantum framework it is therefore necessary to assume the Causality Principle, or some combination of principles that implies it.

On the other hand, one may ask whether the quantum formalism, as we know it, could be extended to new situations in which the Causality Principle has limited validity.

A possible extension consists in having some physical systems that obey the Causality Principle, alongside with some other physical systems that violate it. Considering such an extension means conceding (at least as a thought experiment) that certain system may travel back in time.

Another possible extension is to extend the whole framework, going from a linear connection of events (through the input-output distinction) to some new type of connection.

In the following I will discuss both extensions. For this purpose, it is useful to review two basic properties of the quantum formalism.

6. Quantum superposition

In quantum information theory, the basic unit of information is the quantum bit, or *qubit*.

A qubit is a physical system with two perfectly distinguishable states, |0> and |1>, plus an infinity of other states, often called *superposition states.* Mathematically, the qubit is associated to a two-dimensional complex vector space, and every vector of unit length represents a valid state.

An interesting example of qubit arises in the famous double slit experiment, where a quantum particle can traverse one of two slits

(Feynman, Leighton, and Sands 1965). In this example, the state |0> describes the particle traversing the first slit, while the state |1> describes the particle travelling the second slit.

The superposition states are more difficult to visualize. First, they are not states in which the particle traverses one slit with some probability, and the other slit with the remaining probability. The difference between a probabilistic mixture and a superposition state can be experimentally detected by an interference experiment.

With a bit of poetic license, we could describe the superposition states as states in which a particle "traverses both slits at the same time", although it is important not to take this expression at face value.

An interesting feature of the "double-slit qubit" is that it is not a material system: the qubit is not the particle itself, but rather the abstract system associated to the two alternative trajectories of the particle. At the logical level, we can define a qubit every time we encounter two perfectly distinguishable alternatives. Considering these two alternatives as the basic states |0> and |1>, we can in principle conceive superposition states in which these two alternatives coexist. For example, we can consider a particle in a superposition of two alternative positions, or even a car in a superposition of turning left and turning right.

Whether the superposition states we defined correspond to an experimentally accessible physical depends on the system under consideration, and on the technology available to us. For particles, the superposition states are experimentally accessible. For cars, no superposition state has been observed so far.

Regarding superposition states as a logical construction is useful because it takes us to the heart of one of the most crucial features of quantum theory: entanglement.

7. Entanglement

At the popular level, entanglement is associated to the so-called "Schrödinger's cat" (Schrödinger 1935). In this *Gedankenexperiment*, a cat is in a room containing a vial of poison, and a machine designed to open the vial if a certain radioactive particle decays. The particle can be modelled as a qubit, with the state |0> bringing to no decay, and the state |1> bringing to decay. The design of the machine implies that when the particle is in the state |0> the cat survives, and when the particle is in the state |1> the cat is killed by the poison.

In short, we can represent the implication as:

|0> → |non-decayed particle and alive cat >
|1> → |decayed particle and dead cat >

The interesting situation arises when the particle is in a superposition state. In this case, the particle and the cat are jointly in a superposition state: precisely, a superposition of the states |non-decayed particle and alive cat > and |non-decayed particle and alive cat >.

The destinies of the particle and the cat are, as it were, joined in a single superposition state.

Please don't get distracted by the rhetorical expedient of cat, and by all the folklore that comes with it. The key point here is that the superposition can propagate from a system to another: every time we have an implication like

|0> → |situation X>
|1> → |situation Y>

a superposition of |0> and |1> can in principle lead to a superposition of |situation X> and |situation Y>. This mechanism is general, in the sense that it can be applied no matter what situations X and Y represent.

In the following I will consider the case in which situations X and Y correspond to two different ways to connect two events.

8. The quantum SWITCH

Regarding quantum theory as a new probability theory allows us to apply the superposition principle to new situations. In particular, we can consider the situation in which the two alternatives in superposition are two different causal structures.

The simplest case is the following. Consider two events, A and B. For example, A could be the collision of two particles, and B could be the passage of a photon through a crystal. Classically, we can imagine two alternatives: in one alternative, the event A influences the event B, in the other, the event B influences the event A. In our example, the collision of two particles determine whether or not the photon passes through the crystal, or *vice-versa,* the passage of the photon could determine whether or not the two particles collide. Since we assumed the Causality Principle, the first alternative requires A to occur before B, and the second alternative requires B to occur before A.

Now, the Schrödinger’s cat mechanism allows us consider a new situation in which the causal influence takes place “simultaneously from A to B and from B to A”. This idea is at the basis of the quantum SWITCH, introduced in 2009 by Mauro D’Ariano, Paolo Perinotti, Benoit Valiron, and myself, and published in Physical Review A (Chiribella, D’Ariano, Perinotti, and Valiron 2013).

The quantum SWITCH is a logical operation that connects two events A and B either in the order AB or in the order BA depending on the state of a control qubit, which plays the role of the radioactive particle in Schrödinger’s cat.

From an algorithmic point of view, the quantum SWITCH is a higher-order function. The input of the function SWITCH are two physical processes, A and B, and a control qubit, which determines the order in which A and B are connected. The output of the quantum SWITCH is a new physical process, in which the two processes A and B take place “simultaneously in the two orders AB and BA”.

The quantum SWITCH lets the two processes A and B interact in a new way, which was not possible in the classical world. We can think of A and B as operations executed by two computers. For example, computer A could take an integer number *n* as its input, and increments it by 1, thus producing the number *n+1* in output. Computer B could take an integer number *n* as its input, and double it, thus producing the number *2n* in output.

In this example, the order AB corresponds to the operation that first increments by 1 and then doubles. The order BA corresponds to the operation that first doubles and then increments by 1. Note that the final result changes depending on the order in which the two computers operate.

Now, quantum theory allows us to conceive (at least in prinicple) a new way to use our two computers, by connecting them in a superposition of the two alternative configurations AB and BA.

The mechanism is similar to that of Schrödinger’s cat: a quantum particle, in a superposition of the two states |0> and |1>, controls the choice between two alternatives, thus propagating the superposition to all the systems involved in the interaction.

At this point, it is natural to ask two questions. The first question is which kind of operational consequences arise from this new way of connecting physical processes. The second question is how to realize the quantum SWITCH operation; indeed, quantum theory only tells us that the quantum SWITCH operation is logically possible, but it does not tell us how to realize it in practice.

In the following I will briefly address both questions. I will start from the easier one, about the operational consequences: if someone were to lend us a magical quantum SWITCH machine, what could we do with it?

9. A game

A first indication that the quantum SWITCH enables us to achieve new and potentially useful things came from a work published in Physical Review A (Chiribella 2012). In this example, the quantum SWITCH allows us to win in a game.

The goal of the game is to classify two physical processes, by distinguishing between two alternative hypotheses. The rules are the following: the player is brought to a room, containing two devices, A and B. The behaviour of the two devices is unknown to the player, except for the following promises:

-the two devices act on a given quantum system (for example, a photon), known to the player

-the action of the devices is described by two matrices, A and B, respectively

-one and only one of the following properties holds:

(1) the matrices A and B commute, namely AB = BA

(2) the matrices A and B anticommute, namely AB = - BA.

The goal of the player is to guess which alternative is the correct one. A correct answer makes the player score one point, and a wrong answer makes the player lose one point.

Now, imagine that two players compete for a prize. The player who scores more points wins the prize, while the other goes home empty handed. If we wish, we could even imagine a crueller version of the game, in which the prize is the player’s life.

Imagine that the first player has a machine that connects the two devices in the way described by the quantum SWITCH, while the second player is constrained to use the two devices in a well-defined order, say with A before B. For the first player, who has access to the quantum SWITCH, the win is guaranteed. Using the interference between the two orders AB and BA, the player can discover whether the matrices A and B commute or anticommute. In principle, the player is guaranteed to win every time the game is played: if the game is played for 1000 times, the player will score 1000 points.

For the second player, the situation is less promising. In the original article, I showed that there is no way to win with certainty when the two devices A and B are connected in a definite order. A later work showed that the winning probability is limited by 92.98% (Araujo *et al.* 2015). For 1000 repetitions of the game, this corresponds to an expected score of approximately 929. The difference, of approximately 70 scores, is due to the ability to connect the two processes A and B in a superposition of orders.

The interest of this game is in the fact that it allows us to demonstrate the advantage of the superposition of causal structures in a simple and mathematically rigorous way. The game itself does not have much practical relevance, at least for what we know at the moment.

Following up on these results, other games of similar nature have been proposed (Araújo, Costa, and Brukner 2014). These games employ a version of the quantum SWITCH with more than two processes. For example, one can consider 3 processes A, B, and C, in a superposition of the 6 possible orders ABC, BCA, CAB, ACB, CBA, and BAC. More generally, *N* processes can be connected in *N!* orders, a number that grows exponentially with *N*. The existing results suggest that the advantage of the superposition increases with the number of orders that are superposed. Still, a rigorous quantification of the advantage as a function of *N* has not been provided so far.

10. Applications to the theory of communication

An application of the superposition of order that is closer to practical application concerns the theory of communication. This is a more recent development, published in Physical Review Letters (Ebler, Salek, and Chiribella 2018).

Consider the following situation. A sender wants to transmit a message to a receiver. On the way from the sender to the receiver, the message is forced to traverse two noisy transmission lines, A and B, in which its content is altered. For example, the message could be a sequence of zeros and ones, and the transmission lines could turn some zeros into ones and *vice-versa*. The problem is to find the best way to communicate in the presence of this kind of errors.

In this scenario, the quantum SWITCH offers a rather spectacular advantage. Suppose that the two transmission lines are to completely noisy channels, which erase the message, replacing it with a random sequence of zeros and ones. When the message traverses A and B in a definite order, communication is impossible: as soon as the first transmission line is traversed, the content of the message is obliterated. The situation is radically different when the two transmission lines A and B are combined through the quantum SWITCH. In this case, the message sent by the sender ends up in a superposition of two trajectories, one that traverses channel A before channel B, and one that traverses channel B before channel A. Surprisingly, communication becomes possible, despite the fact that each transmission line is disastrously noisy. Paradoxically, the superposition of two useless channels yields a useful channel.

The secret lies in the correlations between the message reaching the receiver and the qubit that controls the order of the two channels A and B. The net result of the superposition of orders AB and BA is to transfer information from the original message to the correlations between the message and the control qubit. Now, if the control qubit is accessible to the receiver, then the receiver can exploit these correlations to decode the message. The efficiency of the transmission is not too high, but the interesting thing is that, by using a suitable code, the sender and receiver can now communicate.

Another example of this kind concerns the security of communication (Salek, Ebler, and Chiribella 2018; Chiribella *et al.* 2018). We can imagine a scenario in which a message is forced to traverse two regions controlled by spies, corresponding to two insecure communication channels A and B. When the channels are used in a definite order, AB or BA, the resulting channel is insecure. In contrast, when A and B are combined in a superposition of orders, it becomes possible to transmit messages securely.

Examples of this type are abundant. In general, the composition of two noisy communication channels allows us to mitigate, and sometime even cancel the noise.

From the technological point of view, the reduction of noise through the superposition of orders is quite interesting. Several prototype experiments inspired by the quantum SWITCH have been realized at the University of Queensland (Goswami, Romero, and White 2018), the University of Science and Technology of China (Guo *et al.* 2020), and the University of Vienna (Rubino *et al.* 2020). Moreover, the communication advantages of the quantum SWITCH stimulated the interest in new communication protocols where the configuration of the devices is in a quantum superposition (Abbott *et al.* 2018; Chiribella and Kristjánsson 2019; Guerín, Rubino, and Brukner 2019; Kristjánsson, Chiribella, Ebler, Salek, and Wilson 2020).

For the moment, it is worth summarizing what has been discussed so far. Quantum theory allows us to imagine a machine, the quantum SWITCH, that combines two events A and B in two alternative orders AB and BA. This machine offers several advantages. First, it increases our chances to win in certain games, where the player has to find out a property of two unknown processes. Second, the quantum SWITCH increases our ability to communicate through noisy channels.

11. Impossibility of realizing the quantum SWITCH in a standard causal network

It is now time to ask ourselves how the quantum SWITCH could be realized in nature. Remind that the quantum SWITCH was defined abstractly as a function that transforms two physical processes in input into a physical process in output. In general, there may be many physically inequivalent ways to realize the same function.

Let us see first how the quantum SWITCH *cannot* be realized.

For sure, the quantum SWITCH cannot be realized by inserting the two processes A and B in standard causal network, that is, a circuit where time is well-defined and every process is localized in time. The advantages we have seen are already a proof that such realization is impossible. It is also interesting to consider another line of demonstration, presented in the original paper on the quantum SWITCH (Chiribella, D’Ariano, Perinotti, and Valiron 2013).

The proof is by contradiction. Assume that it is possible to realize the quantum SWITCH by inserting the processes A and B in a sequence of processes, in which each process happens with certainty. Based on this premise, one can show that such a sequence of processes, should contain a “time travel”, that is, a process that takes a message in the future and sends it back to the past.

In other words, the realization of the quantum SWITCH in a standard causal network requires the ability to modify the state of a system in the past, in open violation of the Causality Principle. Since standard quantum theory satisfies the Causality Principle, it follows that such a realization is impossible.

On the other hand, if we entertain the idea that the Causality Principle may not hold in certain situations, the quantum SWITCH could be realized in a circuit in which the processes A and B are localized in time, provided that the circuit contains some process that sends the state of a system backward in time.

12. Realization of the quantum SWITCH through a closed time-like curve

A realization of the quantum SWITCH using a time-travelling system was provided in the original article (Chiribella, D’Ariano, Perinotti, and Valiron 2013). In that realization, the processes A and B take place in parallel, and one of the physical systems travels back in time.

In principle, a circuit of this kind could be realized in a spacetime that contains closed time-like curves. Spacetimes of this kind are known in general relativity: a famous example is due to Gödel, who derived a solution of Einstein’s equations where time flows in a cyclic way.

An entirely different matter is whether the universe in which we live corresponds to a solution of this type. In this sense, neither the quantum theory of probability nor the relativistic theory of spacetime give us a direct answer: both theories provide us a spectrum of logical possibilities, but leave our experiments the burden to decide whether or not these logical possibilities are realized in nature.

So far, no experiment has reported any violation of the Causality Principle, or any indication that closed time-like curves exist in some parts of the universe. What we can conclude is that, in the physical regime accessible to our experiments, the past is not modifiable, and the quantum SWITCH cannot be realized by placing processes A and B in a sequence of processes.

13. Experiments with photons

The impossibility of realizing the quantum SWITCH with known physics seems to be in contradiction with numerous experiments performed with photons (Procopio *et al.* 2015; Rubino *et al.*, Goswami *et al.* 2018, Wei *et al.* 2019). The working principle of these is based on ordinary physics, in which time flows in a linear way. How can they realize the quantum SWITCH?

In fact, the experiments are not in contradiction with the impossibility of realizing the quantum SWITCH in a standard causal network. The key point is that the experiments do not utilize two processes A and B that are localized in time, but rather two new processes A′ and B′ that are distributed over time. What the experiments demonstrate is the possibility to simulate the quantum SWITCH with alternative resources that are accessible in ordinary physics.

From the technological point of view, these experiments are important, because they suggest new applications. For example, they show that certain correlations in time allow us to realize the advantages of the quantum SWITCH for communication theory. In the longer term, these experiments could provide the foundation of a new technology of quantum communication networks in which the messages travel in a superposition of trajectories, thus improving the quality of communication. A discussion of this perspective is presented in a recent work published in Proceedings of the Royal Society A (Chiribella and Krisjánsson 2019).

14. Realization of the quantum SWITCH in a quantum spacetime

So far we have seen a radical realization of the quantum SWITCH in a scenario in which time is a classical, well-defined variable, but certain physical systems can travel back in time. A different kind of realization arises when the time order is not a classical variable. Suppose that two processes A and B take place in two spacetime events P and Q, respectively, defined by some suitable operational procedure. Classically, we can imagine a spacetime configuration in which P precedes Q, and another configuration in which Q precedes P. Now if spacetime itself is a quantum system, we can imagine it in a superposition of these two configurations. In this scenario, the qubit that controls the order of processes A and B is the configuration of the spacetime in which the processes take place.

This situation is conceivable in a quantum theory of gravity. Examplea of gravitational realizations of the quantum SWITCH was provided in terms of superposition of massive objects (Zych, Costa, Pikovski, and Brukner 2019; Paunković and Vojinović 2020). In fact, the possibility of having quantum superpositions of spacetime configurations is considered one of the distinctive traits of quantum gravity. In this sense, the search for a physical realization of the quantum SWITCH is intertwined with another fascinating project, namely the search for experimental evidence that spacetime can be in a quantum superposition. Recent proposals by Bose *et al.* at University College London (Bose *et al.* 2019) and by Marletto and Vedral at Oxford (Marletto and Vedral 2019) suggest that experiments of this kind could be realized in the not too far future.

15. Conclusion

Our brief tour of quantum causality has reached its end. Our journey can be summarized as follows. The conceptual core of quantum theory is an extension of probability theory. This extension includes new states, called superposition states, in which alternative classical configurations coexist. When a quantum system is in a superposition state, the interaction with other physical systems can propagate the superposition to them, as highlighted by the Schrödinger’s cat mechanism. This mechanism suggests the in-principle possibility of a machine, called the quantum SWITCH, which connects two physical processes A and B in a superposition of two alternative orders AB and BA, where the order is correlated with the state of a quantum bit.

The quantum SWITCH offers a new resource for information technology. It increases our chances to win in certain games, and it enhances our ability to communicate through noisy transmission lines.

The quantum SWITCH is an abstract operation, and admits radically different physical realization. One of them requires a violation of the Causality Principle, and might be possible if our universe were to contain closed time-like curves. Another, less radical, possibility is that the processes A and B are not localized in time. This realization is compatible with the known physics, in which time flows in a linear fashion and the Causality Principle is satisfied. This realization is at the basis of many recent experiments, in which the superposition of orders is generated by sending a photon along two alternative trajectories, as in the double-slit experiment. Finally, a third realization is possible in a quantum spacetime, in which in principle the processes A and B can be instantaneous, but the relation between the corresponding instants is not well defined. In this scenario, the realization of the quantum SWITCH is intertwined with the search for experimental evidences of the quantum nature of spacetime.

As you might have noticed, the analysis provided in this presentation does not offer answers to the most radical questions *"is it possible to modify the past"* or *"is it possible to observe situations in which the order of two spacetime events is in a superposition?".* In this respect, the abstract theory of quantum probabilities and its extensions only indicate the space of what is logically conceivable, suggesting possible effects that would arise in that scenario. In this context, the research on foundations invites us to explore new frontiers of experimental physics and engineering, with the scope of determining in which of the many logically possible universes we actually live.

I hope that this presentation may have offered an interesting perspective on the topic of this conference, and few stimuli for future discussions. Thank you for your attention.

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