Time-delocalized variables violating causal inequalities

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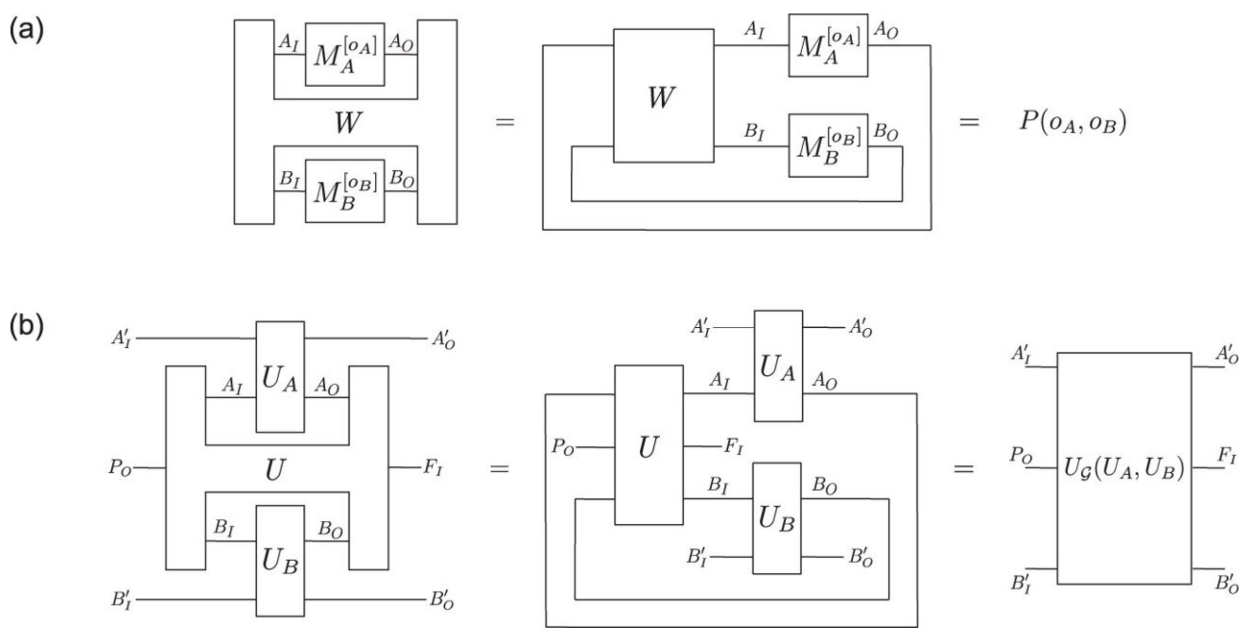

Process matrix scenarios as cyclic circuits. a In the process matrix framework, the operations performed by the parties (here, Alice and Bob) are composed with the process matrix, which defines a channel from the output systems $A_O B_O$ of the parties back to their input systems $A_I B_I$. This composition can be seen as a cyclic circuit, and provides the probabilities for the classical outcomes o_A and o_B. b Composing a unitarily extended process matrix with unitary operations performed by the parties gives rise to a unitary operation from the outgoing system P_O of the global past party P and the incoming ancillas of the parties A'_I,$'_I$ to the incoming system F_I of the global future party F and the outgoing ancillas of the parties A'_O,B'_O. Credit: *Nature Communications* (2023). DOI: 10.1038/s41467-023-36893-3

A team of researchers from the Université libre de Bruxelles and the French National Center for Scientific Research have shown for the first time that an exotic type of process violating causal inequalities can be realized with known physics. A violation of a causal inequality proves under theory-independent assumptions that certain variables in an experiment cannot be assigned a definite causal order.

This is a phenomenon that has been known to be possible in theory, but widely believed impossible in practice, at least in the known regimes of physics. The new study, published in *Nature Communications*, shows that such processes can in fact be realized in standard quantum mechanics using variables that are delocalized in time. The finding may have far-reaching implications for our understanding of causality in physics.

The concept of causality is essential for physics and for our understanding of the world in general. Usually, we think of events as happening in a well-defined causal order. That is, they are ordered according to some time parameter, such that events in the past can influence events in the future, but not vice versa. For instance, the sunrise causes the rooster to crow, but whether the rooster crows does not have any influence on the sunrise.

In recent years, there has been a growing interest in the question of what becomes of this conventional notion of causality when quantum theory comes into play. One of the seminal results in this new field has been the discovery of hypothetical processes that can produce correlations violating so-called causal inequalities, which would imply the lack of causal order between specific variables in an experiment, similar in spirit to the way the violation of Bell inequalities implies that no local hidden variable model can explain the observations.

But while Bell inequality violations rule out classical causal explanations of certain correlations, the variables observed in a Bell experiment still respect the causal structure of spacetime in the sense that they do not allow signaling faster than light. Causal inequality violations, on the other hand, imply that certain observed variables cannot in principle be endowed with a causal order, since some of these variables are in a sense both in the causal past and in the causal future of each other.

Despite significant progress in this field of research, the question of whether processes violating causal inequalities can be realized in the regimes of known physics had remained a central open problem. Although certain causally indefinite processes were known to admit experimental implementations via conditioning the times of events on quantum variables in superpositions, these processes cannot violate causal inequalities, which is a much stronger, theory-independent form of causal indefiniteness. Due to their highly counterintuitive properties, processes violating causal inequalities were commonly assumed impossible with known physics.

Now Julian Wechs and Ognyan Oreshkov, F.R.S.-FNRS researchers at the Université libre de Bruxelles, and Cyril Branciard, CNRS researcher at the Institut Néel in Grenoble, have shown that certain processes violating causal inequalities can in fact be realized in the regimes of standard quantum physics, on so-called time-delocalized subsystems.

These are physical systems defined by observables that are delocalized over different instants of time, much in the same way as quantum information can be delocalized in space, for instance in quantum error correcting codes. The concept has been introduced to test the claim that previous experimental implementations of causally indefinite processes constitute genuine realizations of the theoretical concept.

The researchers have now found a new way of delocalizing subsystems that makes possible the implementation of an unexpected class of causally indefinite processes, among which some very striking examples that violate causal inequalities. They have described a potential realization of one of the most counterintuitive processes known—the so-called Lugano process, discovered by Mateus Araujo, Adrien Feix, Ämin Baumeler, and Stefan Wolf—which is, surprisingly, classical and deterministic, describing cyclic causal dependences between three parties akin to those expected in closed time-like curves.

"This possibility is achieved through a new way of delocalizing quantum or classical operations. The results look as if Alice and Bob can make choices that influence whether a specific action performed once by Charlie takes place in their past or in their future. This is obviously in violation of causality, since they should not be able to influence whether Charlie did something in their past or not. The 'solution' to this apparent paradox is that the operation of Charlie happens neither in the past nor in the future—it happens in a delocalized way over both possible times," explains Julian Wechs, the lead author of the study.

"It is truly mind-blowing that this type of situation is possible in practice, even with time-delocalized variables. Now that we have seen what these variables look like, it seems nonsurprising in retrospect that we can define variables that are delocalized over different times in such ways that they cannot be effectively localized conditionally on other variables. But if you had asked me three years ago whether I believed processes violating causal inequalities could be realized in terms of such variables, I would have probably guessed that they could not," adds Cyril Branciard.

"What I find really striking is that this causal inequality violation concerns entirely classical variables," says Ognyan Oreshkov. "We had known for some time that, at least in theory, noncausal correlations are not an exclusively quantum phenomenon when we have more than two parties. But the fact that this can occur in practice really forces us to reconsider our presumptions about what kind of causal relations are possible in nature. And when quantum superpositions are allowed in the picture, the range of possibilities becomes even wider."

The consequences of this result for our understanding of time are still to be unraveled. Can there be observers for which time flows in a way that corresponds to the cyclic causal relations in this type of process, and could this give hints about the behavior of spacetime in regimes where both quantum theory and general relativity become relevant? Beyond its significance for fundamental physics, the researchers are hopeful that this result could give rise to new applications in information processing that exploit time-delocalized variables.

More information: Julian Wechs et al, Existence of processes violating causal inequalities on time-delocalised subsystems, *Nature Communications* (2023). DOI: 10.1038/s41467-023-36893-3

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