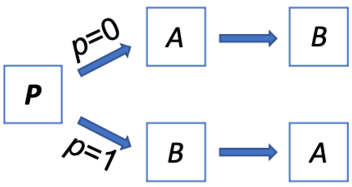
NÉEL INSTITUTE Grenoble

Topic for Master 2 internship – Academic year 2022-2023

Dynamical superpositions of causal orders

General Scope :
Understanding the causal relations between different events that one observes is at the very heart of science. Classically, causal orders are well-defined: e.g., either a single event A can be the cause of another single event B (let's denote it $A < B$), or B can be the cause of A ($B < A$), but not both. Beyond such simple fixed causal orders, one can also envisage dynamical causal orders, where the order between events is not fixed a priori but can depend on past events: e.g., a past event P could decide whether A comes before B (resulting in the causal order $P < A < B$), or vice-versa ($P < B < A$) – cf Figure.



Things become less trivial when entering the quantum world [1]. Considering that the events under consideration are quantum operations, it has been realized that their order can be coherently controlled by a "control qubit", depending on its state $|0\rangle$ or $|1\rangle$, so that the causal order becomes a superposition of the kind (roughly speaking)

$$|0\rangle \otimes |\text{“}A < B\text{”}\rangle + |1\rangle \otimes |\text{“}B < A\text{”}\rangle.$$

This new kind of process, called the *"Quantum switch"* [2], has attracted a lot of interest recently, both for the very fundamental questions it raises on the status of causal relations in quantum theory, and for the new types of applications it allows for in terms of quantum information processing.

Research topic:
Beyond the *"Quantum switch"* above, in some recent work [3] we have introduced new types of quantum processes, that involve both coherent control and dynamical causal orders. This combination of the two features is however still poorly understood. The objective of this internship will be to clarify what dynamical orders really involve. The student will first further investigate dynamical orders of quantum operations by themselves, exploring in which fundamental sense they are different from fixed orders, or how they could bring advantages for certain quantum information processing tasks. In a second step, dynamical order will be combined with coherent control, and we will investigate how exactly this can be understood and characterized.

[1] Č. Brukner, *Quantum causality*, Nat. Phys. **10**, 259 (2014).
[2] G. Chiribella *et al.*, *Quantum computations without definite causal structure*, Phys. Rev. A **88**, 022318 (2013).
[3] J. Wechs *et al.*, *Quantum Circuits with Classical vs Quantum Control of Causal Order*, PRX Quantum 2, 030335 (2021).

Possible collaboration and networking :
There will be close collaborations with Alastair Abbott from Inria Grenoble. This internship also fits in part with a new ANR project obtained in collaboration (in addition to A. Abbott) with Alexei Grinbaum at CEA Saclay and Pablo Arrighi at University of Saclay, with whom networking will also be possible. The student will also work in close contact to the other theory students in our group.

Possible extension as a PhD : Funding is not secured yet, but good candidates can apply and hope to get a PhD fellowship from the Ecole Doctorale, or from the Grenoble Quantum PhD programs (we will help with and support such applications).

Required skills: Good knowledge of the formalism of quantum theory; interest in the foundations of (quantum) physics. Prior experience in the field of quantum information will be a plus.

Starting date : 1st semester 2023

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