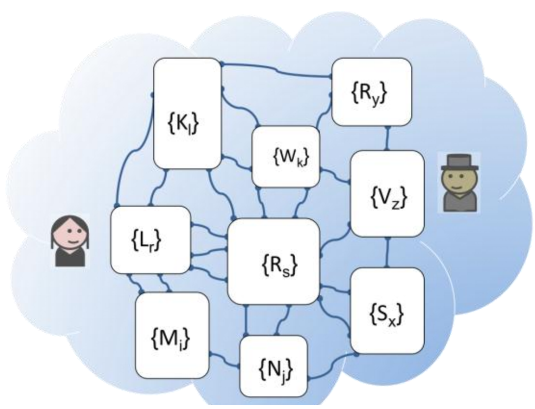
PUBLISHABLE SUMMARY

Marie Curie Intra-European Fellowship, Project QCEC (PIEF-GA-2010-273119)

Researcher: Dr. Ognyan Oreshkov
Scientist in charge: Prof. Nicolas J. Cerf
Host institution: QuIC, Université Libre de Bruxelles, Brussels, Belgium.
Period: 01/01/2012 – 31/12/2013

Quantum information science has revolutionized our understanding of the relationship between physics and information. It has taught us that different physical principles can offer radically different means of information processing, with quantum mechanics allowing informational tasks that are impossible by classical means. This has opened up prospects for novel information technologies, provided we could harness quantum dynamics and develop methods for precise control of quantum systems. At the same time, we have seen that physics itself can be understood via the concept of information, with the mathematical structure of quantum theory being tightly linked to informational principles. This perspective has opened up a new approach to the study of fundamental physics, providing novel insights into areas as basic as quantum gravity.

This project has led to results in quantum information and quantum foundations with potential implications to both quantum technologies and fundamental physics.



The most important outcome of this project is a series of results on the relationship between causal structure and quantum theory. In a paper published in Nature Communications [1], it was shown that it is possible to conceive correlations between local quantum experiments that do not obey definite causal order. Such correlations would allow two parties, Alice and Bob, to accomplish a communication task – the violation of a `*causal inequality*' – which witnesses the incompatibility with definite causal order similarly to the way a violation of a Bell inequality witnesses the incompatibility with local hidden variables. This result was obtained in a new framework for quantum correlations, which can describe local quantum experiments at arbitrary space-time locations, as well as in scenarios with indefinite causal structure, using an object called the *process matrix* which generalizes the standard density matrix. Following this line, we have performed a major study culminating in the development of an operational formulation of quantum theory without any predefined time or causal structure [2]. The key idea is that operations describe information about the possible events in different abstract regions, which can be connected in networks through their boundary systems with no directionality assumed for the connections (see figure). A generalization of Born's rule gives the probabilities for the events in a network. We have shown that the causal structure of space-time can be inferred from properties of the operators in different regions without the need for it to be specified a priori. The framework can also describe exotic causal relations such as those expected to exist in the context of quantum gravity. This work has implications for the foundations of quantum theory, higher-order quantum information processing where the order of black-box operations can be dynamical, as well as for the problem of unifying quantum theory with general relativity [2].

Within the process matrix framework, we have also derived a complete characterization of the so-called causally separable processes, which describe situations in which the individual local operations are embedded in a causal structure, even if their concrete locations in the structure may be unknown. Beyond two operations, this is a non-trivial problem due to the possibility that the causal order between a subset of the operations may depend on the setting or outcomes of other operations taking place in their past. This result classifies the correlations that can be realized by classically controlled quantum circuits, which allows one to identify experimental situations in which the quantum control of the order of operations can offer advantages in communication or computation tasks [3].

We have also obtained theoretical results that offer new tools for the manipulation of quantum information and its protection against noise. We have developed a new theoretical framework for quantum feedback control based on weak continuous measurements, where the target is the implementation of a general quantum operation on a possibly unknown state. We have shown that any feedback protocol can be reduced in a state-independent way to an equivalent Markov process on the space of normalized completely positive maps and have derived an equation describing the stochastic evolution in that space [4], [5]. We have explored methods for quantum control by dissipation, and have developed the gauge theory of a new type of geometric phases that occur in adiabatic Markovian dynamics [6]. We have studied quantum error correction by continuous weak measurements and feedback from the point of view of the structure of protected information, establishing a quantitative link between the problem of protecting unknown information and that of protecting a known state, and have shown how to approach the design of continuous-time error correction protocols from simpler protocols for the protection of a qubit state [7]. We have studied the entanglement-generating properties of an optical beam splitter using the theory of majorization, showing parametric regimes that allow the effect of catalysis [8]. We have written a comprehensive chapter on a fault tolerant scheme for holonomic computation, explaining its workings based on the subsystem structure of information [9].

<u>REFERENCES:</u>

[1] O. Oreshkov, F. Costa, and C. Brukner, "Quantum correlations with no causal order", Nature Communications 3, 1092 (2012).

[2] O. Oreshkov and N. J. Cerf, "Operational quantum theory without predefined time", preprint attached in Periodic Report.

[3] C. Giarmatzi and O. Oreshkov, "Multipartite causally separable processes", in preparation.

[4] M. Bernair (advisor: O. Oreshkov), "A Markovian approach to general quantum feedback control", ULB Master's thesis (2012), attached in Periodic Report.

[5] O. Oreshkov, M. Benair, and N. J. Cerf, "Quantum feedback control for target operations", in preparation.

[6] O. Oreshkov and E. Sjoqvist, "Geometric phases in adiabatic Markovian dynamics", preprint attached in Periodic Report.

[7] O. Oreshkov, "Continuous-time quantum error correction", in *Quantum error correction*, edited by D. A. Lidar and T. A. Brun, (Cambridge University Press, 2013), http://arxiv.org/abs/1311.2485.

[8] C. N. Gagatsos, O. Oreshkov, and N. J. Cerf, "Majorization relations and entanglement generation in a beam splitter", Phys. Rev. A 87, 042307 (2013).

[9] O. Oreshkov, T. A. Brun, and D. A. Lidar, "Fault tolerance for holonomic quantum computation", in *Quantum error correction*, edited by D. A. Lidar and T. A. Brun, (Cambridge University Press, 2013), http://arxiv.org/abs/1312.0165.