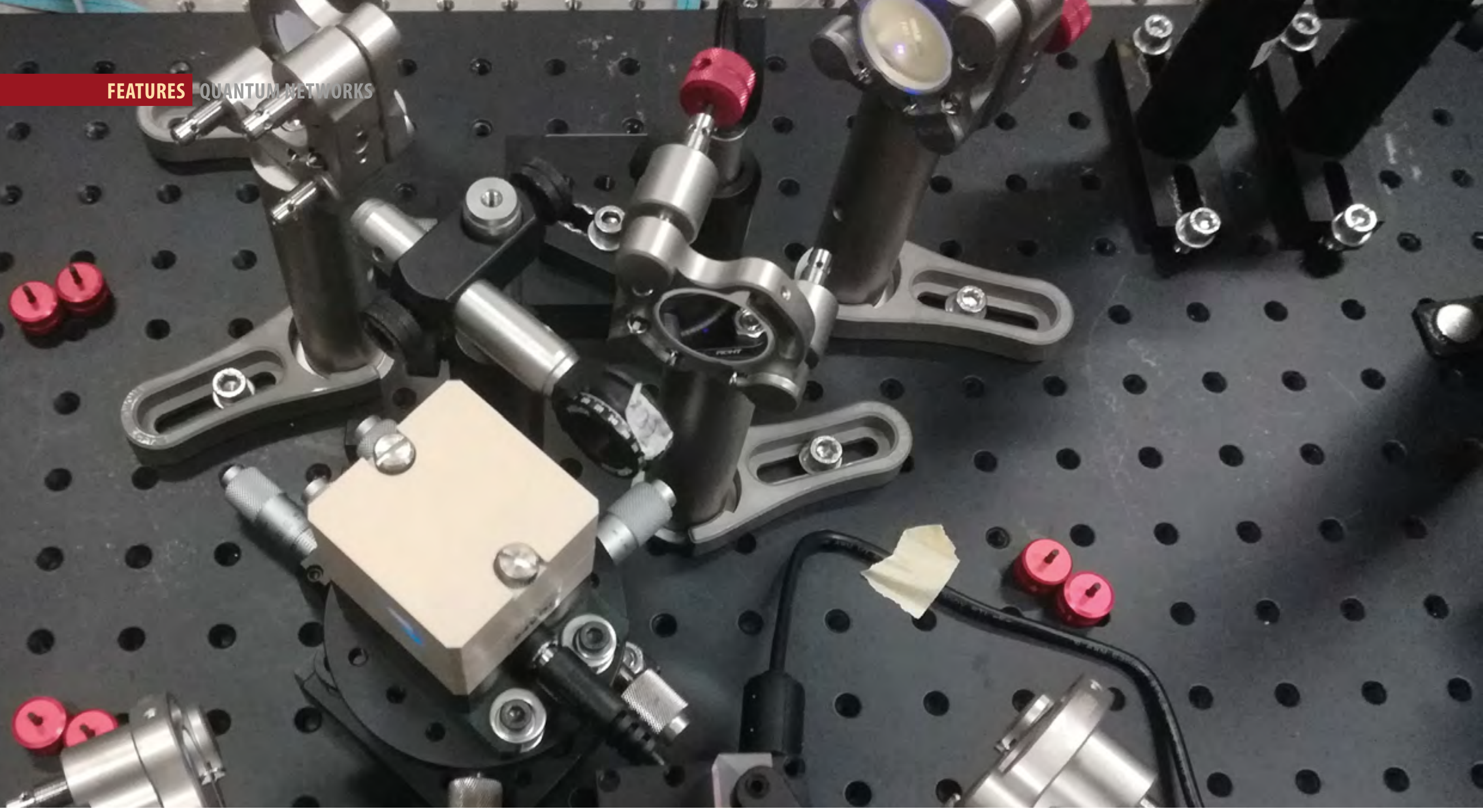


ENTANGLEMENT, CAUSALITY AND QUANTUM NETWORKS

Emanuele Polino and Fabio Sciarrino – DOI: https://doi.org/10.1051/epn/2023105
Department of Physics, Sapienza University of Rome, 00185 Rome, Italy – fabio.sciarrino@uniroma1.it

Quantum nonlocality, generated by strong correlations between entangled systems, defies the classical view of nature based on standard causal reasoning plus physical assumptions. The new frontier of the research on entanglement is to explore quantum correlations in complex networks, involving several parties and generating new striking quantum effects. We present recent advances on the realization of photonic quantum networks.

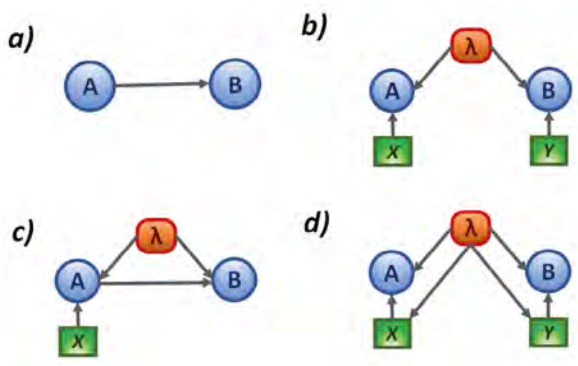
Entanglement and quantum nonlocality

In 1935 Albert Einstein, Boris Podolsky and Nathan Rosen (EPR) challenged the completeness of quantum theory in its standard formulation, presenting the famous EPR paradox [1]. The scientists showed that the assumption of completeness of quantum mechanics, contradicts at least one among two natural assumptions: the locality of influences and a fundamental criterion of reality. At the root of the EPR paradox there is entanglement, the most distinctive phenomenon emerging from quantum mechanics and departing from a classical interpretation of the world. Entangled states of multipartite systems exhibit strong correlations that are maintained regardless of the distance between the parties. Einstein and his coworkers believed that these nonlocal correlations were incompatible with the principle of locality, which states that an influence cannot be transmitted faster than the speed of light. They argued that quantum mechanics should be considered an incomplete description of reality and should be integrated by a more complete theory that incorporates hidden variables leading to a deterministic and local description of physical systems.

Three decades later John Bell demonstrated the impossibility of formulating local hidden variable (LHV) theories that are consistent with all predictions of quantum mechanics [2]. His theorem led to the development of Bell inequalities, which can be experimentally tested to determine whether nature can be described by LHV theories. If Bell inequalities are violated, no LHV theory can provide an adequate description of the observed data. A large number of experimental tests have been conducted so far to verify the predictions of quantum mechanics. These experiments have consistently shown that the predictions of quantum mechanics violate Bell inequalities, demonstrating that LHV theories, satisfying Bell's assumptions, are incompatible with nature.

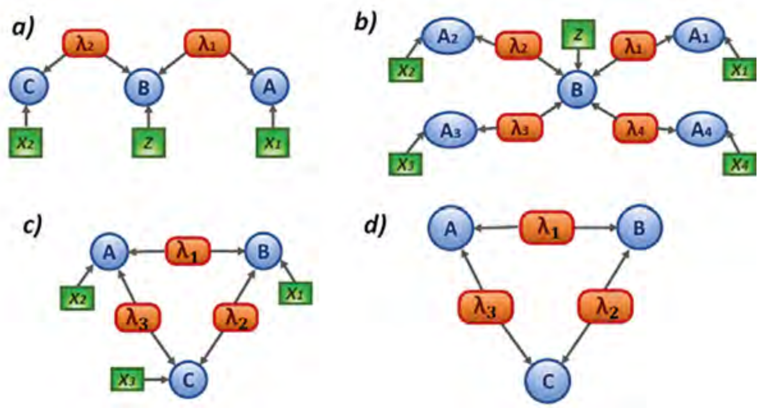
Causal inference and quantum nonlocality

Quantum nonlocality manifests itself through the violation of Bell inequalities that are derived from classical assumptions. Recently, it has been realized that these assumptions can be cast in the classical causal framework. More specifically, Bell theorem requires the so-called freedom of choice in which the measurement choices are statistically independent from the source of the subsystems and the local causality assumption. Local causality is the factorization of probabilities implied by the classical causal model of the Bell scenario, where the correlations of the two systems are required to be entirely explained by the common cause. In this way, Bell theorem can be seen as a particular case of the general causality framework [3]. Here, causal models are mathematically formalized by Bayesian networks, able to treat probabilistic causal relations. They are based on Directed Acyclic Graphs (DAGs) that describe the causal relationships between the variables of the considered scenario [3].



◂FIG. 1: Causal structures. a) Causal arrow between two variables. b) Bell scenario. c) Instrumental scenario. d) Bell scenario without freedom of choice assumption.

The relevant variables, observable or latent, are represented by nodes. Conversely, causal relationships between variables are represented by arrows (Fig. 1a). DAGs are both an explicit graphical representation and a mathematical description of causal modeling. From any causal model, one can directly extract the classical constraints on the probabilities relative to the observable nodes by means of a general factorization rule called Markov condition. For instance, in the Bell bipartite scenario (Fig. 1b), the Markov condition corresponds exactly to local causality. Notably, these constraints depend only on the causal structure and not its specific implementation and the inner structure of the • • •



▲ **FIG. 2:** Causal structures. a) Bilocal scenario. b) Star-shaped network. c) Triangle network with external inputs. d) Triangle network without inputs.

experimental devices. In Bell's scenario the absence of causal arrows between the source and the measurement choices corresponds to the free-choice assumption. Experimental tests try to enforce this assumption using quantum random number generators or even human choices [4] for choosing the measurement settings. When such an assumption is not used, possible influences between the source and the measurements choices (Fig. 1c) could explain Bell inequalities violations. In this case, one can extend the causal structure to demonstrate quantum violation of classical causal constraints [5]. On the other hand, if one allows for causal influences between the two parties, considering the so-called instrumental scenario (Fig. 1d), quantum-classical gaps can be nevertheless found [6,7].

In this way, causal modeling has a twofold utility. First, it helps to clarify the assumptions behind classical models that are violated by quantum correlations. Hence, it represents a powerful tool to study the testable boundaries between classical and quantum realms. Second, it allows the study of classical constraints in general arbitrary causal structures composed by several nodes and sources. Hence, several networks, beyond the bipartite Bell scenario, can be studied in this framework.

Quantum networks beyond bell scenario

The simplest form of nonlocality can be demonstrated in the standard bipartite Bell scenario, where a single source shares subsystems among two distant measurement stations (Fig.1b). There are at least two motivations for considering more general and complex causal scenarios composed of several parties and sources. The first is fundamental: complex networks are able to show new forms of nonclassicality. The second reason is practical: the advantages for quantum communication, brought by quantum nonlocality, will lead to the realization of the future quantum internet connecting several dislocated users. It is then crucial to study which kind of nonclassicality can arise from these scenarios, in order to exploit it for communication tasks. Accordingly, during the last years, an intensive and growing research has been dedicated to face the challenges posed by complex networks coming from both theoretical and experimental sides [8]. We briefly review recent advances on the development of photonic platforms able to show quantum nonclassicality, violating causal constraints in complex networks composed by independent sources.

Bilocal and star-network scenarios

The simplest complex network with more than one source is the bilocal scenario [8]. Here, two independent sources share subsystems among three measurement stations, with a central one receiving subsystems from both the sources, and the two peripheral ones each receiving a subsystem from a source, respectively (Fig. 2a). From the causal constraints, explicit nonlinear Bell-like inequalities can be devised in this scenario. Entangled states and suitable measurements can violate these inequalities contradicting the predictions of bilocal models, that are those models satisfying the causal constraints in the bilocal scenario. Different photonic experiments reached a violation of classical limits using entangled states of light. The first experiments were performed using pairs of polarization entangled photon pairs from two sources pumped by the same laser [9,10]. To enforce the independence of the sources, a demonstration using fully independent sources was realized, also performing the measurements in a space-like configuration [11].

A generalization of the bilocal scenario to an arbitrary number of independent sources is the star-network scenario where n sources share subsystems between a common central node and n peripheral nodes (Fig.2b). A photonic implementation of a quantum star-network has been demonstrated using up to four independent sources and five measurement stations [12].

Triangle scenario

One of the most interesting causal scenarios is the triangle network. Here, three independent sources share pairwise pairs of subsystems among three measurement stations in a triangle configuration (see Fig.2c-d). This seemingly simple scenario shows rich features.

When each node of the network is provided with an external input, requiring the freedom of choice assumption, the nonclassicality of quantum correlations can be demonstrated performing three parallel Bell tests among each pair of nodes of the network. This configuration has been experimentally realized using three entangled photon sources in [13]. The most striking feature of the triangle network is that quantum correlations can show nonclassicality without the use of external input. In this way, the freedom of choice assumption is not needed and is replaced with the independence of the sources. The first experimental demonstration of this new kind of nonclassicality has been recently implemented in [14].

Discussion and perspectives

The nonclassicality arising from entangled states is the most radical departure of quantum theory from classical physics. This nonclassicality can be cast in the violation of classical causal modeling. The causality framework allows to formalize quantum nonclassicality in arbitrary scenarios and in the last years several quantum networks were realized in photonic systems violating classical causal constraints. Several challenges remain to be faced in this research area. From a theoretical point of view, the characterization of the classical-quantum gap in complex networks is a hard task with several open points. From an experimental perspective, networks with different causal structures have to be explored, in particular those in which entangled measurements on subsystems from different sources are performed. ■

About the Authors

Fabio Sciarrino is Full Professor at the Physics Department of the University of Rome La Sapienza and Senior Research Fellow at the International School for Advanced Studies Sapienza. He is Principal Investigator of the Quantum Information Lab (www.quantumlab.it). **Emanuele Polino** is post-doctoral fellow at the Physics Department of the University of Rome La Sapienza funded by the Templeton QISS project.

Acknowledgements

The authors were supported by The John Templeton Foundation via the Grant QISS2 (qiss.fr) Grant Agreement No. 62312, and by the ERC Advanced Grant QU-BOSS (Grant agreement no. 884676).

References

[1] A. Einstein, B. Podolsky, & N. Rosen, *Phys. Rev.* **47**, 777 (1935)

[2] J. S. Bell, *Phys. Phys. Fizika* **1**, 195 (1964)

[3] J. Pearl, (Cambridge University Press, 2009)

[4] BIG Bell Test Collaboration and others, *Nature* **557**, 212 (2018)

[5] R. Chaves *et al.*, *PRX Quantum* **2**, 040323 (2021)

[6] R. Chaves *et al.*, *Nat. Phys.* **14**, 291 (2018)

[7] I. Agresti *et al.*, *Sci. Adv.* **8**, eabm1515 (2022)

[8] A. Tavakoli *et al.* Reports on Progress in Physics (2021)

[9] G. Carvacho *et al.*, *Nature Communications* **8/1**, 1 (2017)

[10] D. J. Saunders *et al.*, *Science Advances* **3/4**, e1602743 (2017)

[11] Q.-C. Sun *et al.*, *Nature Photonics* **13/10**, 687 (2019)

[12] D. Poderini *et al.* , *Nature Communications* **11/1**, 1 (2020)

[13] A. Suprano *et al.*, *PRX Quantum* **3**, 030342 (2022)

[14] E. Polino *et al.*, preprint arXiv:2210.07263 (2022)