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Preface

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Preface of the special issue quantum foundations: information approach

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This special issue is based on the contributions of a group of top experts in quantum foundations and quantum information and probability. It enlightens a number of interpretational, mathematical and experimental problems of quantum theory.

The quantum information revolution has renewed the interest in the foundations of quantum theory, upon regarding the theory from the novel information-theoretical perspective [1–5]. 'Information' is the new paradigm reflecting the main character of modern human society as an *information society*. The tremendous development of information technologies of the last 20 years has dramatically changed our lifestyle through the world-wide web of the Internet and the mobile-connectivity web that have led to the creation of virtual social networks. The new quantum information technologies (quantum cryptography, quantum computing, quantum simulators and networks) have added a new relevant step forward for the information evolution of the mankind.

Unavoidably, the new information culture has deeply influenced the thinking of scientists, and has become a new paradigm in research in quantum foundations. On the experimental side, the new quantum technology has led to closing the quantum efficiency loophole in Bell inequality tests [6,7], thus Bell's hypothesis [8] that the quantum formalism is compatible with a hidden-variable realist interpretation can now be rejected on an experimental basis.

Of course, a non-local or contextual realism is still compatible with quantum theory, as in the case of David Bohm's mechanics, which, however, still fails in reproducing a relativistic covariant theory and in

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describing quantum fields. Moreover, such a non-local realism with *spooky action at distance* is generally considered unnatural, whereas the Copenhagen interpretation in terms of a processes of information exchanges between quantum systems (e.g. photons) and measurement devices (e.g. beam splitters) is largely more popular. As Bohr emphasized, quantum mechanics does not describe quantum systems and processes as 'they are', but correctly predicts the outputs of measurements performed on quantum systems, with measurement apparatuses are treated classically. Niels Bohr writes [9,10]

> This crucial point, which was to become a main theme of the discussions reported in the following, implies the impossibility of any sharp separation between the behaviour of atomic objects and the interaction with the measuring instruments which serve to define the conditions under which the phenomena appear. In fact, the individuality of the typical quantum effects finds its proper expression in the circumstance that any attempt of subdividing the phenomena will demand a change in the experimental arrangement introducing new possibilities of interaction between objects and measuring instruments which in principle cannot be controlled. Consequently, evidence obtained under different experimental conditions cannot be comprehended within a single picture, but must be regarded as complementary in the sense that only the totality of the phenomena exhausts the possible information about the objects.

The new information-theoretical paradigm that emerged from the quantum information experience is perfectly in line with the Copenhagen point of view.

The present special issue is entirely devoted to such approach to quantum foundations. The issue is composed of contributions of world's leading researchers in quantum information and presents viewpoints—both theoretical and experimental—on a number of foundational problems connected to quantum information.

Almost simultaneously with the seminal paper of Lucien Hardy [11], the paper of Chris Fuchs [12] (see also [13,14]) launched the first attack to quantum foundations within the information-theoretic perspective, and started the movement of Quantum Bayesianism (QBism) as a new route to seeking fundamental principles for quantum theory. Along with Fuchs as the leader and creator of QBism, several authors had relevantly contributed to the birth and development of the movement, most relevantly Carlton Caves, Rüediger Schack, Marcus Appleby and David Mermin. The central idea of QBism is that the Born's rule is a quantum version of the Bayes' rule for statistical inference. This also would represent a way to the problem of the Schrödinger cat paradox in terms of a Bayesian subjectivist interpretation of the quantum state notion. The present issue contains two contributions explaining the relation with QBism of the views of the founding fathers of the Copenhagen interpretation Bohr and von Neumann: the review of Blake Stacey [15] and the debate paper of Jan Faye [16].

The works of Lucien Hardy [11] and Chris Fuchs [12] have largely influenced the start of the axiomatization program of Giacomo Mauro D'Ariano [17], which ultimately lead to the derivation of quantum theory from information-theoretic axioms in collaboration with Giulio Chiribella *et al.* [18]. This work then continued with the derivation of free quantum field theory by additional axioms of homogeneity, isotropy, locality, reversibility and linearity of the information processing [19]. As a continuation of this research line in this special issue, we have a joint paper by Alessandro Bisio *et al.* [20]—which addresses the problem of observer invariance in the discrete theories resulting from fundamental principles, and come out to provide models for the Hopf algebra symmetries that are used in quantum gravity.

A discussion of several fundamental problems of quantum foundations is presented in Arkady Plotnitsky's [21]. The article offers an analysis of such concepts as reality and realism, causality, locality and probability, and their roles in quantum theory, from the works of Heisenberg and Dirac to several key contributors to current foundational discussions and debates. This history, the article argues, is defined by the discoveries increasingly complex configurations of observed phenomena and the emergence of the increasingly complex mathematical formalism, accounting for these phenomena, culminating in the standard model of elementary particle physics, defining the current state of quantum field theory. The article reassesses this history, beginning with Heisenberg's discovery of quantum mechanics, in quantum-informational and technological terms. The 2013 discovery of the Higgs boson, predicted by quantum field theory several decades ago, is considered as a dramatic recent example of this history and is also given a quantum-informational and technological interpretation.

The article of Hans De Raedt *et al.* [22] proposes the thesis that the quantum theoretical description of experiments is the organization of experimental data that separates as much as possible the description of the measured system from that of the measurement apparatus.

The issue also contains contributions devoted to development of the mathematical formalism of quantum information theory in connection to foundations, such as the paper of Ole Andersson *et al.* [23], and that of Noboru Watanabe [24]. The notion of quantum randomness plays the crucial role both in quantum foundations and technology: starting with von Neumann's claim about irreducible quantum randomness and reaching through to the current promise of quantum random number generators. Therefore, it is high time for its deeper foundational analysis of the essence of randomness, as in the article of Gregg Jaeger [25]. In this contribution, Jaeger grounds the randomness of quantum mechanics in the context of Schwinger's elegant mathematical reconstruction of the quantum formalism via measurement. Schwinger's reconstruction assumes that fundamental randomness takes place during measurement without deeper grounds; Jaeger shows that the occurrence of outcomes at random in quantum measurement follows from the *Principle of plenitude* as applied to the physical context, thereby bolstering the strengths of the measurement-based approach to quantum theory. In the provocative paper, Elitzur & Cohen [26] claimed that non-events play the crucial role in elaboration of a proper interpretation of some basic quantum experiments.

Quite recently the mathematical formalism of quantum mechanics, especially quantum probability and information, started to be actively used in applications outside of quantum physics: in cognitive studies, psychology, decision-making, economics, finances and politics [27]. The idea that quantum probability and logic might be useful to describe human mind is not new: we can mention, for example, the Pauli-Jung correspondence. However, for a long time the quantum mechanical perspective on cognition was debated mainly in philosophic terms or represented in abstract mathematical models. Nowadays, instead, an increasing number of research groups of psychologists and molecular biologists are working actively with experimental statistical data by using the methods of quantum probability theory. This community (known under the name *quantum interactions*) suffers of the absence of adequate interpretation which would support borrowing the formalism developed for quantum physics. Andrei Khrennikov [28] announced QBism as the most natural interpretation of quantum cognition, as representing the private agent perspective in the process of decision making based on assignment of subjective probabilities. Inter-relation of quantum foundations and psychology was also enlighten in the paper of Ehtibar Dzhafarov *et al.* [29]. Another contribution devoted to application of methods of quantum mechanics outside of physics is the article of Emmanuel Haven [30]. The work of the joint team of physicists, mathematicians and micro-biologists, Masanari Asano *et al.* [31] is devoted to contextual quantum-like representation of classical physical and biological systems. There it is claimed that the quantum formalism can be used to describe stochastic dynamics of macroscopic systems, mechanical as three body system and biological as a cell or genome.

We hope that the reader will enjoy the present issue, which will be useful to experts working in all domains of quantum physics and quantum information theory, ranging from experimenters, to theoreticians and philosophers.

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