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EDITORIAL

Preface

Maria Luisa Dalla Chiara[1] · Roberto Giuntini[2] · Eleonora Negri[1] · Giuseppe Sergioli[2] · Sonja Smets[3]

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Logic, quantum theory and music have for a long time been regarded as disciplines that are far apart from each other. During the last decades, however, we have witnessed an increasing interest for investigations that have focused on possible links and interactions between these separated worlds.

Although quantum theory gave rise, right from the outset, to a number of intriguing logical problems, Birkhoff and von Neumann's celebrated article "The logic of quantum mechanics" (published in 1936) did not immediately arise any strong interest either in the logical or in the physical community. For different reasons, both physicists and logicians did not seem inclined to accept that what had been termed "quantum logic" could represent an "authentic" form of logic that, in some situations, should force us to use rules of reasoning different from the classical ones or else to reconsider the way we had been thinking for so long about the essence of logic. Sceptical attitudes towards quantum logic became weaker and weaker during the second part of the twentieth century. The intense research on the "logico-algebraic approaches to quantum theory" brought into light how the rich and complex abstract structures that emerge in the quantum-theoretic formalism naturally suggest new logical ideas and problems. After Birkhoff and von Neumann different forms of quantum logic have been developed and the "quantum-logical thinking" has successfully interacted with investigations in the fields of fuzzy, dynamic and epistemic logics.

Two basic concepts of quantum theory *superposition* and *entanglement* (which had for a long time been described as mysterious and potentially paradoxical) give rise to some strongly non-classical features both from a physical and from a logical point of view. Quantum superpositions bring about a "strange" divergence between *maximal* and *logically complete* knowledge. As is well known, in classical physics *pure states* of physical systems represent pieces of information that are at the same time maximal (in the sense that they cannot be consistently extended to a richer knowledge) and logically complete (because they determine all relevant properties of the systems under investigation). Accordingly, classical pure states seem to be very close to what Leibniz had called the "complete concepts" of individual objects. Quantum pure states, instead, represent maximal pieces of information that cannot *decide* many important properties of the corresponding physical systems. This is a consequence of the celebrated *uncertainties* that characterize quantum theory. The typical mathematical form of a quantum superposition is a unit vector $|\psi\rangle = \sum c_i|\psi_i\rangle$ living in an appropriate Hilbert space that represents the mathematical environment for the quantum system under investigation (say, an electron or an atom). A superposed pure state $|\psi\rangle$ provides us with probabilistic or incomplete information that leaves indeterminate most of the relevant properties of the system. At the same time, $|\psi\rangle$ essentially refers to alternative states $|\psi_i\rangle$ that determine with certainty other possible

✉ Maria Luisa Dalla Chiara
dallachiara@unifi.it

Roberto Giuntini
giuntini@unica.it

Eleonora Negri
eleonora.negri@unifi.it

Giuseppe Sergioli
giuseppe.sergioli@gmail.com

Sonja Smets
sonsmets@gmail.com

1 Florence, Italy
2 Cagliari, Italy
3 Amsterdam, Holland, Netherlands

properties; the physical system whose pure state is $|\psi\rangle$ might verify the properties that are *certain* for the state $|\psi_i\rangle$ with a probability value that is determined by the "accompanying" number c_i. From an intuitive point of view, a quantum pure state seems to describe a kind of *cloud of potential properties* that might become *actual* when a measurement is performed.

Entanglement represents perhaps the most characteristic "strange" concept of quantum theory; this concept gives rise to a deep conflict with some traditional logical views about the relationship between a *whole* and its *parts*. Let us refer to a simple paradigmatic case. We are concerned with a composite quantum system S consisting of two subsystems S_1 and S_2 (say, a two-electron system). By the quantum-theoretic rules that govern the mathematical description of composite systems, all states of S shall live in a Hilbert space that is the tensor product of the two spaces associated to the two component systems. The global system S is in a pure state $|\psi\rangle$ that determines the states of its parts. Due to the mathematical form of $|\psi\rangle$, the states of S_1 and S_2 cannot be pure: they are represented by two identical *mixed states* that codify a maximum degree of uncertainty. As a consequence, S_1 and S_2 can be described as *indistinguishable* and *entangled* physical objects, because they turn out to satisfy the same probabilistic properties. Any measurement performed by an observer either on S_1 or on S_2 would instantaneously transform some *potential* properties of both subsystems into *actual* properties. The celebrated "Einstein-Podolsky-Rosen paradox" (EPR) is based on a similar physical situation. As is well known, what mainly worried Einstein was the possibility of *non-local effects*: the subjective decision of an observer (who may choose among different *incompatible observables* to be measured on the system S_1) seems to determine the instantaneous emergence of an actual property for the system S_2, which might be "very far" from S_1 (possibly inaccessible by means of a light signal). Interestingly enough, in our days, entanglement phenomena, which had for a long time regarded as a kind of enigma, are currently used as powerful resources even from a technological point of view (for instance in teleportation experiments and in quantum cryptography). Hence, one of the philosophically most intriguing features of the quantum world turns out to be the most powerful computational resource in quantum information theory.

In spite of their apparent "strangeness", both the concepts of quantum superposition and of entanglement can be naturally applied to semantic theories, where *meanings* are supposed to be characterized by some *ambiguous*, *holistic* and *contextual* features, as happens in the case of natural and of artistic languages. Superposed states can be used to represent, in an abstract way, *vague possible worlds* that (unlike classical worlds) can *allude* to a number of alternative possibilities. At the same time, entanglement can allow us to model semantic situations where meanings behave in a holistic way: the meaning of a global expression generally determines the *contextual meanings* of its parts. Like in the case of composite quantum systems, information flows from the *whole* to the *parts* (and not the other way around). And, generally, the meaning of a global expression cannot be reconstructed as a function of the meanings of its parts (against the *compositionality principle*, which is a basic assumption of classical semantics).

Music represents a special example of a field where a form of "quantum thinking" can be applied in a very natural way. Although there is no general agreement about the problematic question "what exactly are musical meanings?", there is no doubt that ambiguity, allusion and contextuality are essential features of musical compositions. Accordingly, both the structure of *musical ideas* (which scores refer to) and the critical relationships between musical and extra-musical meanings can be usefully analysed by using some abstract quantum concepts.

In our days, the general conjecture according to which the quantum-theoretic formalism has a kind of universality, which goes beyond the limits of microphysics, seems to be more and more confirmed. By focussing on the abstract issues that concern the part–whole relationship, contextual features and the mechanisms that regulate the transition of information, be it in linguistic form or musical form, we can benefit from the long tradition of work in microphysics where similar patterns are studied. Similar as in quantum investigations, also when focussing on linguistic or musical information, the interaction between an observer and the observed item plays a crucial role. In essence, the information state of the observer and its interaction with the observed object can indeed show non-trivial correlations of the type that we are familiar with in the quantum world. Quantum ideas are currently applied to many different fields: from cognition and perception theories to psychology, economics and sociology. The articles published in this special issue investigate, from different perspectives, some new trends that have brought into light significant interactions between logical results, quantum-theoretic concepts and a formal analysis of music.[1]

Compliance with ethical standards

Conflict of interest The author Maria Luisa Dalla Chiara declares that there is no conflict of interest.

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