On the time-reversal (a)symmetry of quantum theory

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While unitary evolution is formally compatible with time-reversal invariance, the concept of measurement in quantum theory appears to presume a time arrow, which is reflected in the probabilistic rules of the theory. Here, we analyze this problem from the standpoint of a rigorous operational probabilistic framework. We argue that a preferred time direction enters the standard formulation of quantum theory through the implicit assumption that the procedure for implementing a 'valid' quantum operation can only involve pre-selection of parameters, but no post-selection. Under time reversal, the set of 'valid' operations according to this definition is what in the conventional direction of time amounts to pots-selected operations. The latter set is not isomorphic to the set of standard operations (in particular, it does not obey the property called causality, which standard operations do), which reflects a physical asymmetry between past and future that in ingrained in the standard formulation of quantum theory. To understand the origin of this asymmetry, we reformulate quantum theory in fully time-symmetric terms. The main conceptual step is to adopt a generalized notion of operation, which a priori does not make any assumptions as to whether the realization of an operation involves pre- or post-selection. In this approach, operations are not expected to be up to the 'free choices' of agents, but merely describe knowledge about the possible events taking place in different regions, conditional on information obtained locally. This gives rise to a time-symmetric generalization of quantum theory, which provides an operational and empirically consistent definition of time-reversal symmetry in quantum mechanics, overcoming shortcomings of Wigner's classic argument. However, being an extension of standard quantum theory, the time-symmetric formulation is also shown to admit more general symmetry representations than those possible within the usual formulation. The latter could have potential implications for fundamental physics. We also offer an understanding of the physical time-asymmetry underlying the standard formulation of quantum theory – the fact that that forward in time, without post-selection, we can only realize a restricted class of all possible operations, which is not the case backward in time. We show how this property can be formally understood within the time-symmetric framework as a result of boundary conditions in space-time. It is shown that these boundary conditions also imply the fact that we can have memories of the past but not of the future, thereby linking causality and the memory arrow of time at the level of quantum theory.

Based on "O. Oreshkov and N. J. Cerf, Operational formulation of time reversal in quantum theory, *Nature Physics* **11**, 853 (2015)".