Is it possible to be objective in every physical theory?

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We investigate the emergence of classicality and objectivity in arbitrary physical theories. First we provide an explicit example of a theory where there are no objective states. Then we characterize classical states of generic theories, and show how classical physics emerges through a decoherence process, which always exists in causal theories as long as there are classical states. We apply these results to the study of the emergence of objectivity, here recast as a multiplayer game. In particular, we prove that the so-called Spectrum Broadcast Structure characterizes all objective states in every causal theory, in the very same way as it does in quantum mechanics. This shows that the structure of objective states is valid across an extremely broad range of physical theories. Finally we show that, unlike objectivity, the emergence of local classical theories is not generic among physical theories, but it becomes possible if a theory satisfies two axioms that rule out holistic behavior in composite systems.

This extended abstract is based on [33].

The world we experience every day is classical and *objective*, in that different observers agree on what they see. This contrasts with the quantum world, where observations cause an irreducible disturbance on physical states, and sometimes it is impossible to obtain an agreement between observations [9, 6, 28]. Being the fundamental theory of Nature, quantum theory must explain the origin of the classical and objective behavior out of the very different quantum one. This has always been one of the central issues since the very inception of quantum mechanics. The theory of decoherence [41, 16, 42, 34, 35] made the first steps towards a satisfactory solution of this tension, subsequently improved by the methods of quantum Darwinism [43, 5, 17]. This led to the understanding that in quantum theory there are in fact objective states, in the sense that various observers can determine them without disturbance, and agree on their findings [29]. It is argued that such objective states could indeed be responsible for the objectivity we experience in our everyday life [29, 14]. In this regard, besides quantum Darwinism, the presence of the so-called Spectrum Broadcast States (SBS) [19, 14, 24, 23], arising in many concrete dynamical situations [20, 38, 39, 40, 21, 22, 26, 18, 27], has been proposed as an explanation for the emergence of

Submitted to:
QPL 2019

objectivity out of the quantum world. These are multipartite states of the form

$$\rho = \sum_j p_j \left|j\right\rangle \left\langle j\right|_{\mathrm{S}} \otimes \rho_{j,\mathrm{E}_1} \otimes \ldots \otimes \rho_{j,\mathrm{E}_n},$$

where $\{\left|j\right\rangle\}$ is an orthonormal basis of S, and for every E_k the states $\left\{\rho_{j,\mathrm{E}_k}\right\}$ have orthogonal support. The role of SBS in quantum theory is so strong that two of the authors derived from first principles that *all* objective states in quantum theory *must be* SBS [14].

In this work, for the first time we push the analysis of objectivity outside the boundaries of quantum theory to arbitrary physical theories, using one of the most successful tools in quantum foundations: General Probabilistic Theories (GPTs) [10, 4, 1, 7, 11, 15, 3]. This is particularly important for a twofold reason. First, this enables us to identify which part of quantum mechanics is actually responsible for objectivity at a most fundamental level, by looking at it "from the outside", in a landscape of conceivable alternative physical theories. At the same time this analysis can be used as a test of physical consistency of theories beyond quantum [31, 36], as every extension of quantum theory must still be able to account for objective macroscopic physics. Specifically, we conduct our analysis in physical theories satisfying the axiom of Causality [7], stipulating that information propagates from the past to the future, which in turn implies a no-signaling condition in space [7, 8].

Is objectivity a general feature of all causal theories? The answer is negative: we construct a theory, based on a classical trit with a restriction on the allowed effects, which shows *no* objective features.

The emergence of objectivity is tightly linked to the emergence of classicality, as classical physics is objective. For this reason, it is necessary to study how classical theory arises from a given theory. This is crucial because in any physical theory, agents performing experiments in a laboratory interact with the devices through classical physics: the outcomes of experiments are classical data that can be read from pointers in the devices. Every fundamental physical theory should explain how those data are generated out of the internal dynamics of the theory itself. For this reason, when a theory admits a classical sub-theory, we look for a decoherence process that transforms the original theory into that classical sub-theory, imposing only *minimal* requirements, unlike in [32, 25], where a more restricted definition is proposed. Surprisingly, we find that a decoherence always exists in causal theories, and that the measurement process provides a canonical way to completely decohere a generic system and make it classical, as it happens in quantum theory. This shows that the act of observation is inexorably associated with the emergence of classical behavior.

Then we address the core issue—the emergence of objectivity—by recasting it as a multiplayer game. In this game, the players act independently (whence the Strong Independence condition [14, 33]) to determine the state of a target system without disturbing their joint state. The players are restricted to performing a special kind of measurements—sharply repeatable measurements [33, 30]—that guarantee that when the measurement is performed multiple times, the outcome is always the same. We find that all objective states, i.e. states for which the players can win the game, are SBS, viz. classical-classical states, like in quantum theory. This very general result shows that the emergence of objectivity is *widespread* across physics, and not a phenomenon that can be only explained within quantum theory.

The advantage of our approach is the minimality of assumptions about GPTs: we only require Causality, in conjunction with the principle of *Emergence of Classical Concepts* (ECC) [33], which guarantees the presence of classical states in a theory. The latter is not satisfied by the theory of restricted trits mentioned above [33].

Condition 1 (Emergence of Classical Concepts)**.** A fundamental theory must have classical states (or arbitrarily good approximations thereof).

These two very general principles, augmented with the Strong Independence condition, also imply that objective states have the same form—the SBS form—in all theories. This very general result suggests two things. First, that objectivity is widespread in physics, therefore we can conjecture it to be even *necessary* to do physics. Second, the fact that all objective states are classical states suggests that classical theory is indeed a *necessary* interface between observers and the physical world, otherwise no observers could agree on their findings. We conjecture that the scope of quantum Darwinism might go beyond quantum theory, and that we can study "Darwinism" (no longer *quantum* Darwinism) as a general paradigm for the emergence of classicality in *any* physical theory, and even more strongly, to do physics.

Finally, we address how classical theory can emerge locally in a multipartite setting. If we take ECC seriously, classical sub-theories should be classical also in the way they compose, viz. the classical sub-theories in a composite system should all be reducible to the (classical) composition of the classical sub-theories in the subsystems. In order to guarantee this, Causality is no longer sufficient, but it is enough to impose two axioms enforcing a sort of "locality condition" in the emergence of classicality (see [33] for more details).

Axiom 2. *The product of two pure states is a pure state.*

Axiom 3 (Information Locality [12])**.** *If* $\{\alpha_i\}_{i=1}^{d_\mathrm{A}}$ *is a pure maximal set*[1] *of* A*, and* $\{\beta_j\}_{j=1}^{d_\mathrm{B}}$ *is a pure maximal set of* B*,* $\{\alpha_i \otimes \beta_j\}_{i=1,\ j=1}^{d_\mathrm{A}\ \ d_\mathrm{B}}$ *is a pure maximal set of* AB.

In words, these axioms guarantee that, as far as classicality is concerned, "the whole is the sum of its parts". Note that it is possible to construct theories that violate the two axioms explicitly [2, 13].

In conclusion, our results support the approach to objectivity presented in [20, 14, 38, 39, 40, 26, 21, 22, 18, 27] based on SBS, recently shown to be stronger than the notion of quantum Darwinism [24]. Our results extend the validity of this approach far beyond the limits of quantum mechanics. They also suggest that other approaches to the transition to classicality, such as quantum Darwinism and the associated broadcasting of information to the environment [37], could be extended to GPTs, opening a fruitful new research avenue for both the community working on quantum Darwinism and the one working on GPTs and quantum foundations.

There are some open questions for future work. For instance, we showed that the most physically-motivated form of decoherence arises from a measurement in every physical theory. There the environment is present implicitly through the observer who performs the measurement. It is therefore natural to study when a decoherence process involves the *explicit* presence of an environment, and what role this environment plays in the emergence of classicality.

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[1] A pure maximal set is a set of pure states of a theory such that they are distinguishable with certainty in a single shot, and such that no other pure state can be added while keeping them jointly distinguishable.

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