Perceived objectivity via strong quantum Darwinism and spectrum broadcast structure

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The quantum-to-classical transition remains an open problem in foundational quantum mechanics. To make some headway into understanding the transition, we first must define what it means to be "classical". Here, being "classical" is defined in terms of being "objective": we say that a system state property is *objective* if it is (1) simultaneously accessible to many observers (2) who can all determine the state independently without perturbing it and (3) all arrive at the same result [1–3].

This definition lies at the core of quantum Darwinism [2] and spectrum broadcast structure [3]. These two frameworks extend upon decoherence theory and explain how the redundancy of classical information comes about. First, decoherence theory describes how quantum superposition states evolve into statistical mixtures and defines the particular pointer basis into which systems decohere [4–6]. In the parlance of (quantum) Darwinism, system states in the pointer basis are the "selected" states under the dynamics of decoherence. Objectivity occurs when the information about the system in this basis is "reproduced" into multiple different independent fragments of the environment.

Within quantum Darwinism, the emergence of objectivity is marked by the condition that the quantum mutual information $I(\mathcal{S}:\mathcal{F})$ between system $\mathcal{S}$ and fragment $\mathcal{F}$ is equal to the system entropy $H(\mathcal{S})$—or at least approximately so: $I(\mathcal{S}:\mathcal{F}) = (1-\delta)H(\mathcal{S})$. This must occur for fragment sizes $|\mathcal{F}|$ that are sufficiently *small* fractions of the environment, such that there are multiple copies of information in the environment.

Within spectrum broadcast structure, the emergence of objectivity is marked by the condition that the system-fragment must have a particular classical-quantum state structure, $\rho_{\mathcal{SF}} = \sum_i p_i |i\rangle\langle i| \otimes \rho_i^{F_1} \otimes \cdots \otimes \rho_i^{F_k}$, where $\left\{\rho_i^{F_k}\right\}_i$ are mutually distinguishable.

However, these two frameworks *are not equivalent*, despite the same underlying motivating definition of objectivity. Moreover, recent work suggests that quantum Darwinism can falsely signal objectivity: the conditions of quantum Darwinism can be fulfilled for some entangled states [3]; the quantum mutual information $I(\mathcal{S}:\mathcal{F})$ can be comparably comprised of classical *and* quantum correlations [7, 8]; and quantum Darwinism can apparently emerge even when spectrum broadcast structure does not [8].

We resolve these tensions by defining *strong Quantum Darwinism.* Strong quantum Darwinism makes the distinction between classical and quantum information that was lacking in the original formulation of quantum Darwinism. Shared quantum mutual information is not sufficient for objectivity: rather, shared *classical* accessible information $I_{acc}(\mathcal{S}:\mathcal{F})$, given by the Holevo quantity $\chi(\mathcal{S}:\mathcal{F})$, is necessary: $I(\mathcal{S}:\mathcal{F}) = I_{acc}(\mathcal{S}:\mathcal{F}) = \chi(\mathcal{S}:\mathcal{F}) = (1-\delta)H(\mathcal{S})$. The classically accessible information is complementary to quantum discord $\mathcal{D}(\mathcal{S}:\mathcal{F})$ [9], by which we can write $I(\mathcal{S}:\mathcal{F}) = \chi(\mathcal{S}:\mathcal{F}) + \mathcal{D}(\mathcal{S}:\mathcal{F})$. Hence, the condition of strong quantum Darwinism also implies that quantum discord must be vanishing if objectivity is to emerge.

We prove that strong quantum Darwinism is equivalent to spectrum broadcast structure. Furthermore, strong Quantum Darwinism addresses all the concerns mentioned above—it does not falsely signal objectivity.

The difference between traditional quantum Darwinism and strong quantum Darwinism highlights the intuition that objectivity and classicality should depend on the amount of *classical information* that spreads and is shared, rather than the *quantum* information per-se. Moreover, quantum discord hinders the emergence of objectivity by causing the disturbance of the system whenever observers measure their fragment [10–12].

With the fundamental equivalence between strong quantum Darwinism and spectrum broadcast structure, we now have consistent information theoretic and geometric tools to further explore the emergence of objectivity and the quantum-to-classical transition.

[1] H. Ollivier, D. Poulin, and W. H. Zurek, Phys. Rev. Lett. **93**, 220401 (2004).
[2] W. H. Zurek, Nat. Phys. **5**, 181 (2009).
[3] R. Horodecki, J. K. Korbicz, and P. Horodecki, Phys. Rev. A **91**, 032122 (2015).

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[4] E. Joos and H. D. Zeh, Z. Phys. B Condens. Matter. **59**, 223 (1985).
[5] M. Schlosshauer, Rev. Mod. Phys. **76**, 1267 (2005).
[6] M. Schlosshauer, (2014), 1404.2635v1.
[7] G. Pleasance and B. M. Garraway, Phys. Rev. A **96**, 062105 (2017).
[8] T. P. Le and A. Olaya-Castro, (2018), in preparation.
[9] M. Zwolak and W. H. Zurek, Sci. Rep. **3**, 1729 (2013).
[10] H. Ollivier and W. H. Zurek, Phys. Rev. Lett. **88**, 017901 (2001).
[11] L. Henderson and V. Vedral, J. Phys. A: Math. Gen. **34**, 6899 (2001).
[12] K. Modi, Open Syst. Inf. Dyn. **21**, 1440006 (2014).