Quantum Measurements and the Typicality of Objective Reality

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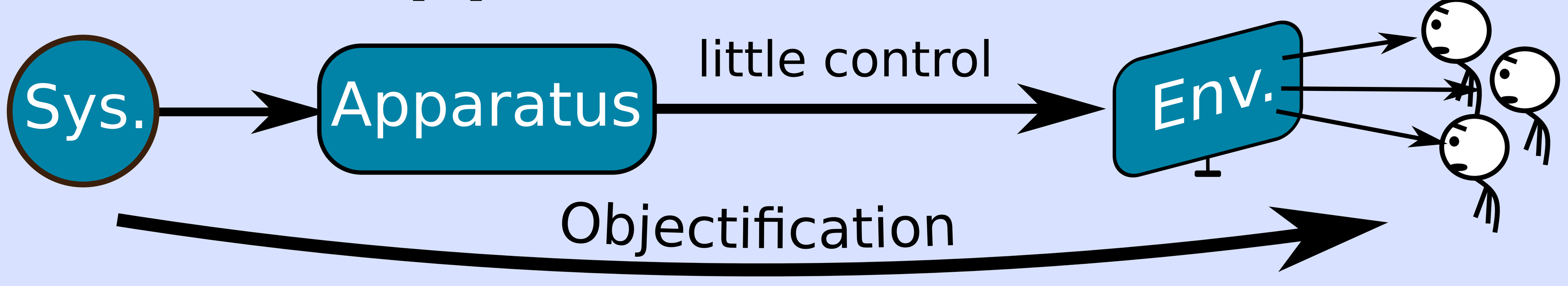
Textbook QM allows for two distinct kinds of dynamics: unitary evolution and measurement. Projective measurements are often treated as instantaneous events that prepare a state perfectly. However, **perfect projective measurements contradict the third law of thermodynamics** [1]. In this work we consider **measurement as an equilibration process**, associated with an entropy increase instead of a decrease. Whenever a measurement is performed the information about the system needs to become **redundant** (*i.e.* objective) and **stable** (*i.e.* in equilibrium). Our question: *Under which conditions does objectivity result from equilibration?*

Measurements & Entropy

$$\rho \xrightarrow{\text{meas.}} |i\rangle \xrightarrow{\text{unitary}} |0\rangle$$

Ideal projective measurements are Unitarily equivalent to ground state cooling, requiring an **infinite amount of resources** [1].



Information about the system has to become:

1. **Redundant** (*i.e.* objective)
2. **Stable** (*i.e.* in equilibrium).

Question: *Under which conditions does objectivity emerge as a result of equilibration?*

Objectivity & Spectrum Broadcast Structure

We model measurements explicitly: a system interacts with an environment consisting of N initally uncorrelated parts.

$$\rho(0) = \rho_{s,0} \bigotimes_{k=1}^{N} \rho_{k,0}$$

A system's state is objective if it is **simultaneously accessible to many observers** who can all determine the state **independently** without perturbing it, and **all arrive at the same result [2, 3].**

There exists a class of states which implies objectivity: **Spectrum Broadcast Structure**

$$\rho_{\text{SBS}} = \sum_i p_i \, |i\rangle\langle i|_{\text{s}} \otimes \bigotimes_k \rho_k^{(i)}$$

$$\rho_k^{(i)} \rho_k^{(j)} = 0 \;\; \forall i \neq j$$

Requiring strong independence (SI) in addition to objectivity results in equivalence to SBS:

$$\text{Objectivity + SI} \iff \text{SBS}$$

Stability & Time-Averaging

The equilibrium state of a system is given by its **infinite-time average** [4].

$$\rho_{\text{eq}} = \langle \rho(t) \rangle_\infty = \lim_{T\to\infty} \frac{1}{T} \int_0^T \rho(t) dt$$

Under which conditions does the total state equilibrate to the spectrum broadcast structure?

$$\langle \rho(t) \rangle_\infty \; \underset{\text{coarse-graining?}}{\xrightarrow{H_{\text{int}}?}} \; \rho_{\text{SBS}} \;\; ?$$

Approachability of SBS

1. There exists no Hamiltonian that takes a full rank state to the SBS exactly, *i.e.*

$$\nexists \;\; H_{\text{int}} \;\; st. \;\; \langle \rho(t) \rangle_\infty = \rho_{\text{SBS}}$$

2."Standard measurement Hamiltonians" [5] don't correlate the environment with the system:

$$H_{\text{int}} = X_{\text{s}} \otimes \sum_k Y_k \;\; \Rightarrow \;\; \langle \rho(t) \rangle_\infty = \rho_s \otimes \rho_E$$

3. More general conditional Hamiltonians, *i.e.* of the form

$$H_{\text{int}} = \sum_i |i\rangle\langle i| \otimes \sum_k c_k H_k^{(i)}$$

can lead to states that approach SBS exponentially in the size of the coarse-grained environments.

$$\langle \rho(t) \rangle_\infty = \sum_i p_i |i\rangle\langle i|_S \bigotimes_q \rho_q^{(i)}$$

where $\tilde{\rho}_q^{(i)} = \bigotimes_{k \in N_q} \rho_{k,0}^{(i)}$ and $F(\tilde{\rho}_{q,0}^{(i)}, \tilde{\rho}_{q,0}^{(j)}) \to 0$

Outlook

Incorporating "pre-measurement" into the picture to account for "disturbing measurements".

Investigate the role of the environment's temperature

[1] Y. Guryanova, N. Friis, and M. Huber, Ideal projective measurements have infinite resource costs, Quantum 4, 222 (2020).
[2] R. Horodecki, J. K. Korbicz, and P. Horodecki, Quantum origins of objectivity, Physical Review A 91 (2015)
[3] T. P. Le, A. Olaya-Castro, Strong quanum darwinism and strong independence are equivalent to spectrum broadcast structure, Phys. Rev. L(2019)
[4] C. Gogolin, J. Eisert, Equilibration, thermalisation, and the emergence of statistical mechanics in closed quantum systems, Rep. of Prog. in Phys. (2016)
[5] P. Busch, P. J. Lahti, The standard model of quantum measurement theory: History and applications, Found. of Phys. (1996)